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HYDROLOGIC ASPECTS

OF

NORTHERN PIPELINE DEVELOPMENT

A series of 16 reports

Glaciology Division
Water Resources Branch
Department of the Environment

for the

Environmental-Social Program
Northern Pipelines

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The data for this report were obtained as a result of investigations carried out under the Environmental-Social Program, Northern Pipelines, of the Task Force on Northern Oil Development, Government of Canada. While the studies and investigations were initiated to provide information necessary for the assessment of pipeline proposals, the knowledge gained is equally useful in planning and assessing highways and other development projects.



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Summary Technical Report

on

HYDROLOGIC ASPECTS OF NORTHERN PIPELINE DEVELOPMENT

by

D. K. MacKay

Technical Report to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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HYDROLOGIC ASPECTS OF NORTHERN PIPELINE DEVELOPMENT

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INTRODUCTION

Hydrologic factors can be of considerable importance in the selection of routes for proposed oil and gas pipelines linking the hydrocarbon reservoirs of Alaska and the northwest mainland of Canada with southern markets. The Canadian section of any such pipeline would cross many rivers and watersheds between the Yukon-Alaska boundary or the Mackenzie Delta and the southern limits of the Mackenzie River Valley (Fig. 1). Some of the rivers and basins pose greater risks from a hydrological point of view than others and, in some areas, the cumulative effect of such risks could suggest that one pipeline route alternative is better than another or, conceivably, that all proposed routes should be abandoned in favour of a new one.

The general intent of our studies is to assess the magnitude and acceptability of the hydrological risks inherent in pipeline construction and maintenance within the broad Mackenzie River Valley and the northern sector of the Yukon Territories. Further, the intent is to offer meaningful advice in the selection or abandonment of particular pipeline routes. In a more specific sense, the objectives of our hydrologic studies can be met through:

a) measurement of extreme flood and ice shove levels on rivers;

b) determination of the location and character of river ice jamming;

c) collection of river scour and fill data;

d) documentation of bank stability and slope failure; and

e) examination of the watershed characteristics and hydro-climatic processes affecting pipeline development in the North.

The substance of both routine and special data collection and analysis is engendered in the assessment of the hydrological risk. Such an assessment relies to some degree on the experience of the research personnel involved. The acceptability of the risk and the possible environmental consequences must be weighed against the many other considerations related to the environmental-social impact of northern oil and gas development.

Our research into the hydrologic aspects of northern pipeline development is necessarily incomplete due to the vastness of the area to be studied, the large number of rivers and lakes within it and the fact that some investigations such as studies of extreme events are time dependent. Some of the gaps that

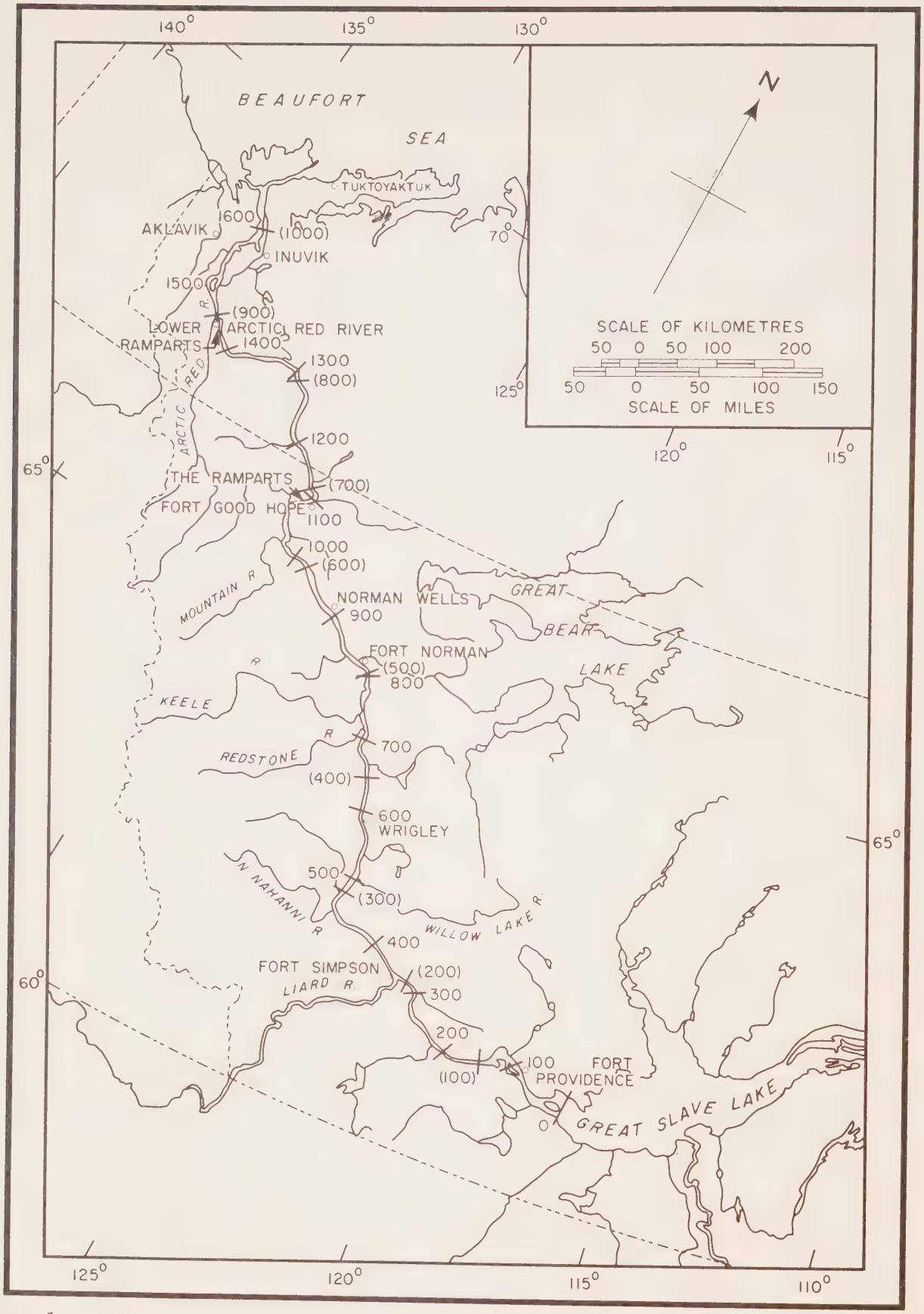


Figure 1. Major tributaries of the Mackenzie River, with locations and distances in kilometres (miles) from the head of the Mackenzie

exist reflect difficulties in obtaining research personnel with sufficient field experience and knowledge to carry out projects in arctic and sub-arctic environments.

The body of this report is a collection of research papers on the hydrology of areas and events considered to be of major concern in pipeline route selection. This introductory paper is designed to explain and summarize in very simplified form, the conclusions and recommendations contained in the body of the report and the more obvious implications of some of the results.

METHODS AND SOURCES OF DATA

A variety of methods common to field work in the physical sciences were used in gathering data for this report. A primary phase involved aerial reconnaissance and air photo examination of areas of potential hydrologic risk. In this way, vast areas of relative unconcern were screened out and sites were chosen where research could prove beneficial to the Environmental-Social Program. The diversity of the research program is reflected in the methodology. Hydrometric and land surveys, instrumental observation of hydrologic and climatic variables, soil sampling, coring and sectioning of trees, aerial photography, detailed map studies and other techniques were used in various measure. An effort was made to use all available hydrologic and meteorologic data in the realization of our objectives.

Experimental techniques entered into some aspects of the research program, principally in the river scour, dendrochronology and frost-heave studies. For example, the susceptibility of a variety of Liard River soils to frost heaving was tested with a new apparatus for measuring pore water pressures (11). Again, relatively new X-ray densitometry techniques for the analysis of thin sections of increment cores were used to yield, through comparison, tentative master tree-ring chronologies (5), (10). Correlations of tree rings with hydroclimatic variables could prove of benefit in the extension of hydroclimatic records and possibly provide us with a history of extreme events.

Examination of river scour proved to be a difficult problem to approach because no data on bed scour of northern rivers are available. Although bathymetry exists for the Mackenzie and parts of its delta, it is insufficiently detailed or lacks the exactness of survey control required to measure changes in river beds over some time base. The examination of river cross-sections derived from Water Survey of Canada discharge measurements yielded inadequate results as discharge is not always measured at identical points either in the cross-section or along the river.

A possible method which may be useful in scour studies is the mapping from air photos of false parallax caused by the flow of water mixed with ice. Ridge and trough effects caused by varying current speeds in a stretch of river are especially pronounced in air photos taken at break-up when ice wreckage and brash are running. A map of false parallax may be regarded as a "signature" of the bed configuration as it is translatable into surface current speeds. Any change from break-up to break-up, assuming a similar river stage, should be an indicator of changes in the bottom configuration. Once changes are detected, the bathymetry in the reach can be remapped and scour and fill properly assessed.

General data analysis followed standard procedures and work was phased according to priorities established by essentially rational but subjective means.

RESULTS

Many of the results obtained are not reported here; only those bearing directly upon pipeline route selection, construction and maintenance are noted in this summary. For detailed results, the reader is directed to the individual studies.

Rivers: general characteristics including ice action and flooding

An aerial reconnaissance of Mackenzie basin rivers, including potential pipeline crossing sites and major problem areas, was carried out under contract. The results include descriptions of the general character of river stretches, some comments on the practical aspects of river crossing construction as well as recommendations for long-term program development of hydraulic and geomorphic studies in the Mackenzie Basin (9).

In addition to a general reconnaissance, specific problem studies (5), (7), (8), (10), show that both the Liard River in its lower reaches as well as the Mackenzie River below its junction with the Liard are subject to high-flood and ice-shove levels during spring break-up. Ice action and flooding have reached as high as 17 m above summer water levels on the Liard and 10 to 15 m above June water levels on the Mackenzie. Mackenzie levels are much lower above the Liard junction with the exception of one location on the north side of Green Island (5).

Ice jamming is prevalent on the lower Liard and on the Mackenzie below Fort Simpson. Surveys show that the recurrence of jams is a fairly regular feature at some river sites while jamming in other reaches may be random in character (8).

In the Mackenzie Delta, point measurements of discharge were made in a number of channels both in summer and in winter. In conjunction with ice thickness data, a preliminary examination of the seasonal distribution of flow through the delta and of delta flooding have been completed (3).

Channel banks and approaches

Two types of mass movement were examined in the Fort Simpson/Liard River area. One type, which is also the most prevalent, is the surficial sloughing and collapse of river banks. The second is a translational/rotational type of bank failure which ordinarily is a relatively large-size feature (4).

In the Little Chicago/Arctic Red River area, 18 slopes were investigated 10 of which were retrogressive flow slides and the remaining 8 were steep colluvial slopes. The flow slides were all associated with the melting of permafrost and 8 of the 10 were triggered by fires (4).

Soil samples at a number of locations along the banks of the Liard and Mackenzie Rivers were analyzed for susceptibility to frost heaving. Two sites, one on the Mackenzie at Martin Island and the other at the Liard River

Ferry crossing, proved to be mantled by soils with high frost susceptibility. Some distance above the Liard Ferry crossing at a large slump, and again at Swan Point near Nahanni Butte, the soils were less susceptible to heaving and from this aspect more favourable for pipeline routing (11).

Watershed characteristics

As the regime of a river is greatly influenced by its basin physiography, systematic morphometric analysis was carried out using measures of linear, areal and relief aspects of channel networks. The morphometric data were extracted from topographic maps of 1:250,000 scale. To date, a total land area of 391,000 km^2 (151,000 sq. miles) comprising 54 primary drainage basins has been covered between the Liard and Peel watersheds and on both sides of the Mackenzie River. The resulting numerical data have been used in the analysis of geomorphic differences between watersheds. For basins in which adequate hydrometric data are available, multiple regression analysis was performed to measure the influence of significant geomorphic parameters on peak flow characteristics. These results were used to estimate peak flow characteristics of ungauged basins which could include several river crossings (14).

In addition to office studies, elements of the water budget are being measured in three research basins. Two of these are located on the east perimeter of the Mackenzie Delta and the other is situated about 320 km (200 miles) directly south of Inuvik, N.W.T., where the Arctic Red River flows out of the northerly front of the Mackenzie Mountains. This latter watershed, Twisty Creek, may be characterized as a sub-arctic upland type which is frequently subjected to orographically-induced summer storms. These storms produce heavy rain resulting in extremely rapid runoff of storm excess waters in upland catchments (12).

On the east side of the Mackenzie Delta, a tundra basin, Peter Lake, and a mainly taiga-covered watershed, Boot Creek, are compared primarily with respect to their hydrologic regimes. Both basins have been subject to disturbance by either fire or other means and are ideally located for environmental impact studies. Among other findings, base flow in Boot Creek has shown a rising trend towards the end of the open season (2).

Hydroclimatic aspects

A general study of precipitation characteristics at meteorological stations along proposed pipeline routes indicates a relatively low frequency of storms which could produce floods. There appears to be little regional variability of precipitation, but it must be pointed out that most data are collected in lowland areas along principal rivers and not in mountainous areas (13).

The occurrence of an extreme summer rainstorm in the Mackenzie mountains is examined from the point of view of the atmospheric processes involved and for its hydrologic and geomorphic consequences. The probability of recurrence of such an event in any year is considered to be less than one per cent; however, smaller yet still significant storms are a yearly phenomenon (6).

An attempt has been made to predict monthly components of the water balance for large sub-basins of the Mackenzie drainage system (1). Estimations of these components could prove useful, for example, in synthesizing streamflow on rivers such as the Hare Indian and Keele or others lacking gauging stations. Results to date are encouraging.

DISCUSSION

Some gaps in the Mackenzie hydrologic research program are more apparent than real. For instance, the omission of a specific study on aufeis (icings) simply reflects our view that the present distribution of the phenomenon is relatively insignificant in terms of pipeline construction. Only occasional patches on Yukon coastal rivers, as well as a scattering in the Richardson Mountains and in the Norman Wells region are located in the vicinity of proposed pipeline routes. Semi-permanent snow banks in the northern stretches may pose greater problems, particularly for hot oil pipelines, than will known concentrations of aufeis.

Icings may become more relevant if, in the process of pipeline construction, the flow in the active layer is disturbed or interrupted. Active layer blockages and ponding of water on the up-slope side of pipelines could result from a proposal to refrigerate gas in pipelines passing through high ice content areas in permafrost. If the gas is not refrigerated or a hot oil pipeline is constructed through high ice content soils, then differential ground settlement and ponding could occur in these areas. Such effects on the permafrost regime may be intolerable from an environmental point of view.

Another apparent gap in the hydrologic program is the lack of research related to rivers draining watersheds on the east side of the Mackenzie River. Many of these streams, however, have fairly stable flow regimes due in part to the ballasting effect of lakes in their systems. Another factor accentuating the stability of these river regimes is the limited relief and the consequent lack of orographic-convectional storms which affect the west side Mackenzie tributaries so profoundly. In the lower reaches of east-side tributaries, where pipeline crossings are proposed, maximum flood levels may be caused by back-water effects of the Mackenzie during spring break-up. The examination of precipitation frequencies and intensities at low-lying Mackenzie Valley meteorological stations (13) suggest there are few extreme events of a character which would aggravate the relatively stable runoff from these streams.

An important concern is the lack of basic information about the varied physical limnology of lakes and bogs along pipeline routes. Some shallow lakes and bogs would, no doubt, be crossed by large diameter pipelines or gathering systems and a refrigerated gas pipeline would have vastly different effects on water bodies than would a hot oil pipeline. The consequences of such crossings, particularly in permafrost areas, are unknown. However, efforts are being made to collect baseline data on the physical characteristics of a number of lakes in the Mackenzie Delta region and in lakes to the south.

Undoubtedly, there are many pipeline concerns where the role of water is not yet fully understood or is not fully recognized by investigators. Many of these concerns are in the realm of permafrost hydrology with all its implications for the fundamental processes in the hydrologic cycle. In spite of the gaps in our knowledge of northern hydrology, we have carried out sufficient

research and collected enough data to draw some conclusions about northern pipeline development.

CONCLUSIONS

The major conclusions of our studies are listed in brief form under the appropriate sub-headings.

Rivers: general characteristics including ice action and flooding

Underground pipeline crossings of the Arctic Red River below Sainville River junction, and of the Peel River between Fort McPherson and Trail River should (on the basis of preliminary reconnaissance) pose relatively few special river engineering problems (9).

The Mountain, Keele, Redstone and North Nahanni Rivers, principal west-side tributaries of the Mackenzie, will be difficult to cross by road or pipeline because of engineering problems associated with the wide floodways, shifting channels, unstable banks and alluvial deposits that are subject to scour (9).

Aerial reconnaissance suggests crossings of the Mackenzie between Arctic Red River and Norman Wells would not appear to pose special problems (9).

Pipeline or road crossings of the lower 60 km of the Liard River and of the narrower stretches of the Mackenzie River between Fort Simpson and the Delta are exposed to high levels of ice jamming, flooding and ice action during the break-up season (5), (7), (8), (10). Such conditions are principally due to the highly variable discharge regime of the Liard River.

Above the Liard junction, the Mackenzie River is relatively stable of flow, somewhat late in break-up, and has low ice shove-driftwood limits with few major jam sites. At and below the Liard junction, Mackenzie River break-up generally occurs earlier on a more rapidly rising stage with significantly higher levels of ice shove-driftwood and numbers of jam locations. The flow from the Liard River more than doubles that of the Mackenzie River, putting tremendous pressure on its ice cover, possibly, when shore leads are ill-developed and ice still shorefast in sections. The strength of the Mackenzie River ice cover combined with the great ice and water inflow from the tributaries contribute to high ice shove-driftwood limits and ice jamming from Fort Simpson down to the Mackenzie Delta (7), (8).

In high-water years, the size of ice jams may increase but their number decreases; conversely, in low-water years, jams increase in number but their size is limited (8).

Ice jams recur quite regularly at a number of sites while at others, recurrence may be infrequent or rare. New sites develop as the channel regime is changed by events such as slumping of banks, landslides, ice jams and normal fluvial processes of erosion and sedimentation. Because of these possibilities, or other random happenings a reach of river or a portion of it may have an aggrading character in one year and be subject to scour effects in another (8).

Ice jams and the high levels of ice action along the banks of the Mackenzie River in some reaches below the Liard River junction down to the Delta indicate the existence of hazardous conditions for both underground or over-river pipeline crossings. The prevalence of ice jamming causes unknown and constantly changing river scour and fill conditions; the height of jamming and unknown ice pressure factors create formidable problems associated with bridging the river for both pipeline and highway construction. The Mackenzie crossing near Cameron Point (kilometre 400-403; mile 250-252) is a known ice jamming site (8).

Dendrochronology is a significant aid in determining ice shove levels through analyses of injuries to trees and in dating ice jams and landslides along channel banks (5), (10).

The distribution of flow in the Mackenzie Delta is greatly altered by the formation and development of an ice cover. In winter, the proportionate volume of flow is less than expected on the west side of the delta (3).

Cross-sectional channel area, width, mean depth and mean velocity can be represented as functions of discharge in the form of simple power equations. Cross-sectional area is the best predictor in the Mackenzie Delta (3).

Channel banks and approaches

Based on aerial reconnaissance, several river stretches between Norman Wells and Fort Simpson appear critical due to bank stability problems; this applies not only to river crossings but also to routes running parallel to the river. The ground, for some distance back from the Mackenzie, is subject to large-scale shallow slides particularly in the more susceptible areas, namely:

a) around Ten-mile and Halfway Islands;

b) from upstream of Police Island to the Keele;

c) around McGern Island (Willowlake River); and

d) Camsell Bend to Martin River.

Unexplained large-scale slides occur as isolated phenomena in otherwise stable well-vegetated banks (9).

In the Fort Simpson region, banks may have to be stabilized at construction sites either by the use of retaining structures or by levelling to a safe inclination. When possible, there should be minimum removal of and interference with vegetation (4).

In areas where unconsolidated deposits are underlain by less permeable deposits, care should be taken to ensure good drainage of water-bearing strata lest pore-water pressures attain critical values. This must be guarded against, particularly in areas where there is melting of permafrost (4).

On both sides of the Mackenzie between Little Chicago and Arctic Red River, vegetation and surface layers should not be disturbed since this will promote rapid melting of permafrost. This is particularly important in areas of glaciolacustrine deposits (4).

Ice content of permafrost should be assessed and compared to the consistency limits of the materials derived from the melting of the permafrost. If the ice content exceeds or is close to the liquid limit of the material, then the possibility of mudflows and retrogressive failures is quite high (4).

If construction is to take place along river banks, then tree-ring inspection along the route may reveal the presence of intermittent movements of slope materials, the possibility of progressive failure of the earth materials as well as possible correlations of earth movements with time (4), (5), (10).

Soil pore pressure measurement is a useful technique for determination of frost-heaving susceptibility of Mackenzie Valley soils and could be of value in the determination of pipeline route selection (11).

Watershed characteristics

Of 33 defined characteristics, the significant morphometric parameters of value in estimation of peak flows seem to be geographic location, drainage density, mean elevation, drainage area, slope, length ratio and the hypsometric profile of the watershed. However, no more than three of these parameters proved of value in peak flow estimation due to limited sample size and to regional inconsistencies (14).

Drainage density defined as the total length of stream channels per unit area appears to be much lower for basins on the east side of the Mackenzie than for basins on the west side of the river (14).

On an equivalent unit area basis, the flood magnitudes of east-side Mackenzie River tributaries appear to be lower than those on the west side of the Mackenzie (14).

Mean elevation of all east-side basins analysed to date does not exceed 300 m (1,000 ft) which suggests a lower potential flood hazard than in tributary basins on the western side of the Mackenzie River where the mean elevation ranges between 500-1000 m (1500 - 3500 ft) (14).

Preliminary hypsometric analysis indicates that all the basic profiles of the rivers on the east-side studies to date seem to be in equilibrium, whereas some adjustment of slopes could take place in the tributary basins on the west side (14).

In the sub-arctic alpine environment of "Twisty Creek", storm excess waters appear as runoff very rapidly although the rate may have been slowed by extensive talus and interflow in solution cracks in the carboniferous rocks. The computed lag time for Twisty Creek catchment is 2.5 hours (12).

In Boot Creek, primarily a taiga basin, direct runoff following a storm appears to be minimal, possibly because of high depression storage in hummocky terrain and high retention capacity of the peat layer and of mosses as well as other types of vegetation (2).

In Boot Creek, base flow is observed to increase in late summer; the reasons for it are not clear (2).

Hydroclimatic aspects

Elements in the development of the devastating 1970 summer storm in the Mackenzie Mountains were the presence of cold air aloft, vertical instability, and a synoptic-scale disturbance superimposed on thermal advection. The highest unit storm runoff values were exhibited by the Arctic Red River; using the Creager envelope curve equation, the coefficient "C" has the value 35 (6).

On braided mountain streams, summer storms may be more significant in causing flood plain changes than are break-up and spring runoff (6).

Storms such as that of July 1970 in the Mackenzie Mountains suggest very real hazards for pipeline crossings and construction on the west side of the Mackenzie River (6).

On the east side of the Mackenzie River, precipitation events greater than 15 mm (0.6 in) water equivalent in 24 hours are rare. There is, moreover, little variation in the pattern of precipitation in all regions for which data are available along possible pipeline routes. It should be made clear, however, that meteorological stations are widely separated and data for some areas is non-existent (12).

Many other conclusions, in addition to those listed, have been arrived at by the authors of the individual research reports. It should be noted that the implications of all conclusions have been assessed in making the recommendations for Mackenzie pipeline route development.

IMPLICATIONS AND RECOMMENDATIONS

General Scientific Recommendations

A long-term program of studies on the hydraulic and geomorphic characteristics of northern rivers should be initiated to ensure the existence of a research and data base for future northern development (9). Such development could involve construction of pipelines and related activities.

The Mackenzie Delta, from a hydrological point of view, is certainly the most complicated region affected by oil and gas exploration in northern mainland Canada. As such, it should be studied and monitored intensively in order that the exploitation of hydrocarbons will have a minimal impact on the ecosystems and on the critical delta environment.

Documentation of water budget components and lake characteristics in a variety of basin environments should be continued and expanded for baseline information purposes. The physical limnology of northern lakes has been neglected and requires a strong research effort.

Pipeline recommendations

The most favoured general route from a hydrological viewpoint is illustrated in Figure 2.

The west side of the Mackenzie River should generally be avoided. However, if a pipeline consortium chooses the west side, then storm runoff and its effect on river floodplains should be documented for a number of extreme events.

The lower crossing of the Mackenzie River would best be carried out between the Lower Ramparts and Point Separation.

A pipeline route east of the Mackenzie River is favoured because of the inherent stability of flow of the east-side Mackenzie tributaries.

The upper crossing of the Mackenzie River would most favourable be located above the Liard River junction. This would significantly reduce the magnitude of risks associated with break-up, ice jamming and ice scour. There, relatively stable flow at break-up limits ice shove and flood levels although back-water effects may control stage directly above the confluence of the Liard and Mackenzie Rivers.

A pipeline crossing between Fort Simpson and Camsell Bend may be subject to severe ice jamming, excessive river and bank scour and massive slumping of banks.

Researchers' views

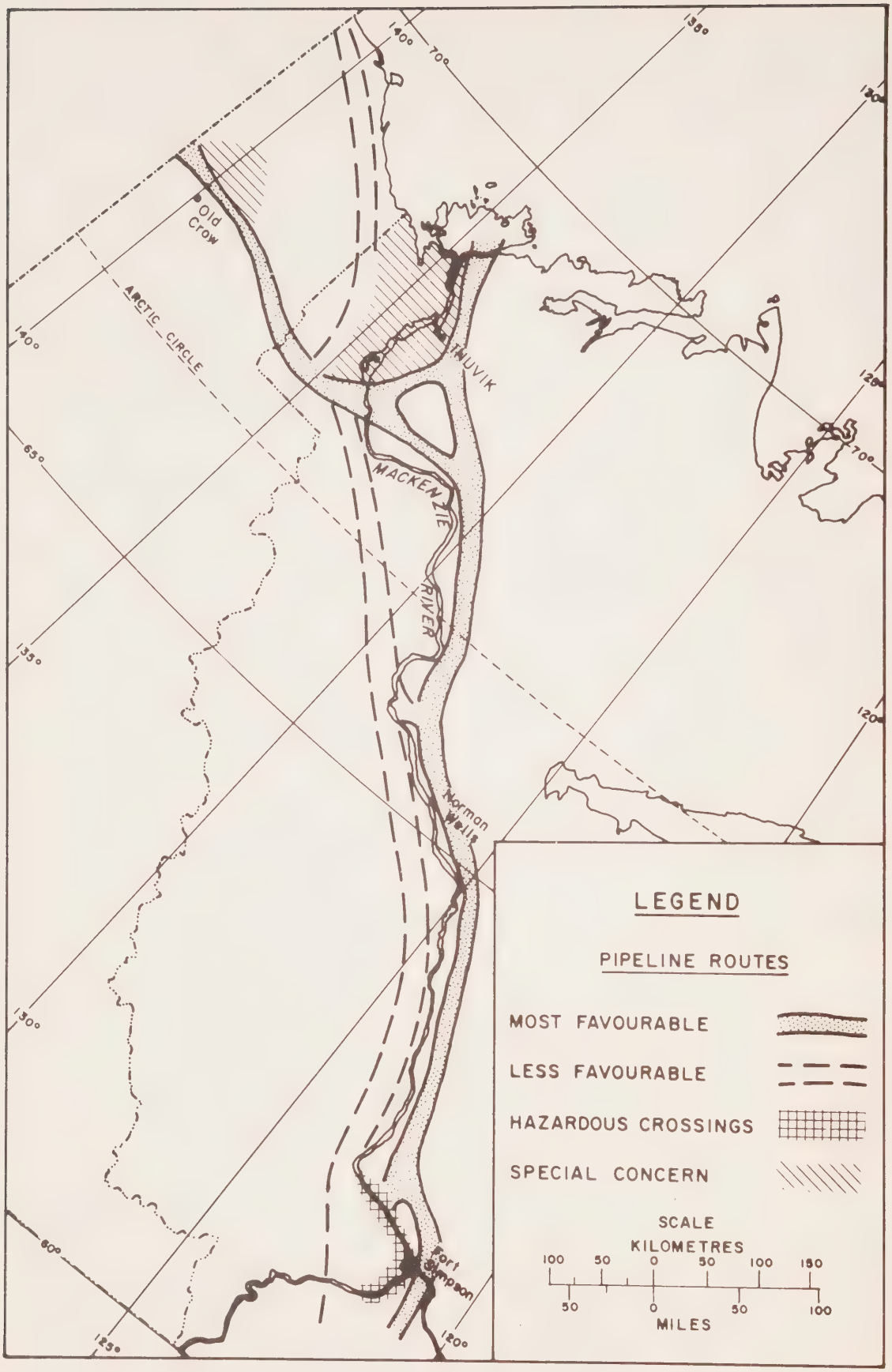
The mountain or interior route through the Yukon would appear to be preferable to the coastal inshore route for reasons of aufeis, the braided character of streams, and the ice content of soils.

Bank and channel erosion and scour by ice action during break-up may cause sediment loads comparable to or exceeding that caused by localized construction and embedding of pipelines at river crossings.

During Mackenzie break-up and other high flow stages, back-water may affect the lower reaches of east bank tributaries. The high sediment load introduced into these tributaries may exceed that caused by pipeline construction at stream crossings.

Beaded streams are a good indicator of high ground ice content in near-surface materials and should be studied more intensively than heretofore.

Many of the hydrological studies carried out under the current Environmental-Social Program should be included in any program designed to evaluate pipeline development in the Arctic Islands and eastern mainland Canada.


Old Crow
ARCTIC CIRCLE
INUVIK
MACKENZIE RIVER
Norman Wells
Fort Simpson
140°
70°
135°
130°
120°
63°
60°
125°
LEGEND
PIPELINE ROUTES
MOST FAVOURABLE
LESS FAVOURABLE
HAZARDOUS CROSSINGS
SPECIAL CONCERN
SCALE
KILOMETRES
100 50 0 50 100 150
50 0 50 100
MILES

Undoubtedly, many other comments about the hydrological aspects of northern pipeline development could be made in this paper. At the present stage of our northern research, it would be premature to speculate further on the interactions of pipelines and water.

ACKNOWLEDGEMENTS

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MACKENZIE BASIN WATER BALANCE STUDY

by

John C. Anderson

Technical Report 1 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

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Northern Pipelines

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ABSTRACT

A water balance model developed by Heinz Lettau is being experimented with and used to predict the monthly water balance components for large sub-basins of the Mackenzie River basin. Three modifications to the original model are discussed, and results are given. The third modification is observed to produce an improvement in the prediction of annual water balance components. Future research will lie in obtaining more reliable predictions of these parameters on a monthly basis.

MACKENZIE BASIN WATER BALANCE STUDY

John C. Anderson

INTRODUCTION

A water balance model developed by Heinz Lettau is being experimented with and used to compute the components of the water balance on a monthly basis for large sub-basins of the Mackenzie drainage basin. Since a detailed discussion of the mathematics of the model has been given by Lettau (1969), only the alterations made to the model by the present author, as well as some of the results, will be noted in this report.

The original model as proposed by Lettau (hereafter referred to as the Lettau model) requires monthly totals of precipitation, net all-wave radiation, and global solar radiation for the basin. Five additional input parameters are required: surface albedo, delay time, evaporivity threshold value of precipitation and ratio of immediate discharge. In return, the model predicts the monthly values of runoff, evapotranspiration and change in the amount of soil moisture. All water balance quantities are expressed in millimetres of water.

For these preliminary experiments, basins which have discharge measurements have been selected so that the runoff predictions of the model can be compared with measured values. This is the only way to assess the accuracy of the model. When found to be functioning satisfactorily with these test basins, the model can then be used to extend or synthesize discharge records for basins where data are scarce or non-existent. Data so obtained would be useful in pipeline construction, for information both on the average monthly discharges to be expected at major river crossings along the pipeline route and on the seasonal water supply for construction camps and future settlements.

EXPERIMENTATION AND RESULTS

During initial experimentation with the model, it was decided to divide the precipitation input into its main components of rain and snow, and to introduce these separately (Anderson, 1971). Rain and snow could then be treated individually, in accordance with their differing hydrologic behaviour. For example, the delay time between a snowfall event and the resultant runoff is longer than the delay following a rainfall event. This is due to the additional time required for snowmelt to occur. Due to the severity of the winter season in the Mackenzie basin, the delay time between snowfall and snowmelt can be several months. Therefore, the snowmelt function adds a vital degree of realism to the Lettau model, especially when the model is applied to basins that experience severe winter conditions.

In keeping with the nature of the Lettau model, a comparatively simple snowmelt function has been employed. It is:

$$SM(t) = S(t)\cdot[SNOW\ (t) + SP(t - 1)]\cdot\{[DD(t)]\ /\overline{DD} + F(t)/\overline{F}\} \qquad (1)$$

where $$F(t) = [1 - A(t)]\cdot G(t)\ . \qquad (2)$$

The variables are defined as follows:

SM = snowmelt

S = snowmelt parameter (dimensionless)

SNOW = snowfall

SP = depth of snowpack (water equivalent in mm) at end of previous month

DD = a degree-day function

F = absorbed global radiation

A = surface reflectivity (albedo)

G = global radiation

t = any one month

All calculations in the model are performed for one hydrologic year (October to the following September) at a time. The overbar in equations (1) and (2) signifies the mean of the 12 monthly values for any one hydrologic year. The degree-day function DD is simply the number of days in the month during which the maximum temperature is greater than 0°C. Values for S(t) are obtained in the same manner as are those for evaporivity. One simply experiments with the parameter, altering its values until the monthly predictions are satisfactory.

Depth of the snowpack is corrected at the end of each month by subtracting from it the amount of snow which melted during the same month. Snowmelt for each month is added to the rainfall of the same month to give the total amount of water available for runoff, evapotranspiration and soil moisture change. In this simplified approach, sublimation from the snowpack is assumed to be included as part of evapotranspiration.

Note that snowmelt will equal snowfall for any one water year, except when snow occurs near the end of the year, especially in the final month, September. If S(t) is less than unity, a portion of the snow cannot melt in the same month in which it occurs. Since unmelted snow is not carried from one water year to the next, snowmelt will fall somewhat short of snowfall in such a case. The problem is not serious, however, for there is normally little, if any, snow during the last months of the water year over much of the Mackenzie basin.

Annual runoff and evapotranspiration are calculated at the outset. The dryness ratio D is defined as:

$$D = R/LP \qquad (3)$$

where R is annual net all-wave radiation, P is rain plus snowmelt and L is the latent heat of vaporization of water. Using an empirical relationship,

$$C = 1 - \tanh D, \qquad (4)$$

the runoff ratio C is obtained. The runoff ratio is defined as C = N/P, where N is annual runoff. With C and P known, N = C.P, and annual evapotranspiration follows as:

$$E = P - N. \qquad (5)$$

In this last equation, a zero change in water storage is assumed. Once the values of E and N are known, they are used to compute monthly totals of evapotranspiration and runoff (Lettau, 1969, pp. 694-696). Thus, it is important that E and N be estimated accurately.

To obtain E and N, monthly net radiation data are required, or at least a total of net radiation for the year, so that R can be obtained. Unfortunately, such data are lacking for the Mackenzie basin. The closest recording site is Edmonton, but no data exist for it prior to 1967.

Thus, an alternative source of information has been sought. From a study by Hare and Hay (1971), mean annual net all-wave radiation data have been used to approximate the actual year-to-year totals. These means have been computed using semi-empirical models of the component fluxes of net radiation (Hare and Hay, 1971, p. 83).

The model has been run for five water years for each of the Athabasca, Hay and Liard River basins. The annual totals of net radiation chosen were 33, 27 and 25 kly, respectively, for these basins. Monthly and annual components of the water balance were calculated, and the predictions of annual runoff are given in Table 1, under the heading "Lettau and snowmelt".

For the Athabasca and Liard River basins, the dryness and runoff ratio method used by Lettau underestimates runoff consistently, sometimes by more than 100 percent. Predictions for the Hay River basin are also poor, being both too high and too low. For the Liard River basin, the value of annual net radiation was altered by up to 30 percent, and predicted runoff was still too low. The error was, therefore, attributed to the empirical relationship between C and D [equation (4)], and a different method of predicting annual runoff and evapotranspiration was tried.

Turc (1954) has developed an empirical equation for computing evapotranspiration. It is:

$$\bar{E} = \frac{\bar{P}}{[0.9+(\bar{P}/I_T)^2]^{1/2}} \qquad (6)$$

where $\bar{E}$ is mean annual evapotranspiration (mm) and $\bar{P}$ is mean annual precipitation (mm). The quantity I_T is defined as:

$$I_T = 300 + 25\bar{T} + 0.05\bar{T}^3 \qquad (7)$$

where $\bar{T}$ is the mean annual air temperature (°C). Note that this formula yields a mean annual value, and not a total for any one year. However, Turc claims that if a negligible change in water storage from year to year is assumed, the formula may be used to predict evapotranspiration for any one year. The assumption of a zero change in storage has already been made, so the equation has been adopted in the model. An advantage of the Turc equation is that no net radiation data are required.

Results obtained with the Turc equation are listed in Table 1 under the heading "Turc and snowmelt". In all cases, and especially for the Hay River basin, runoff is overestimated. A reason for such poor results could be the input data themselves. The precipitation values used in these experiments are obtained by weighting data from all available recording stations in and near the basin. Thiessen polygon networks are employed for this purpose. Unfortunately, precipitation recording stations are lacking at higher elevations in mountainous parts of the Mackenzie basin. Since precipitation is usually assumed to increase with elevation, low-altitude data obtained for mountainous basins such as the Liard must considerably underestimate actual basin precipitation. Similar difficulties are encountered in trying to arrive at a single temperature input which is to be representative of basins as large as the Athabasca, or as mountainous as the Liard. No doubt, the use of inaccurate precipitation data has also had an impact on the results obtained when Lettau's dryness and runoff ratio method was used.

Currently, a third method of computing annual runoff is being developed. It is founded upon the existence of strong linear relationships between annual evapotranspiration (E) and annual precipitation (P) which are observed to occur for the Athabasca, Hay and Liard River basins (Fig. 1). The general equation is:

$$E = aP + b \qquad (8)$$

where a and b are numerical coefficients. Annual evapotranspiration data are obtained by subtracting observed annual runoff from observed annual precipitation. Of course, both runoff and precipitation data must be available in order to develop equation (8). For basins without runoff data, it is suggested that the regression equation will have to be borrowed from a nearby basin which has the data, and hence the equation.

Because of the high correlation that is found to exist between annual evapotranspiration and annual precipitation, the prediction of annual runoff is much better using the regression equation method as opposed to Turc's equation or Lettau's method. (See the column marked "regression and snowmelt" in Table 1). Further refinements to the model appear necessary however, before accurate month-to-month predictions of the water balance components can be achieved.

Table 1. Predicted versus observed annual runoff for the Athabasca, Hay and Liard River basins, using three modifications of the original Lettau model

Water Year	Drainage Basin	Annual Runoff (mm) Observed	Lettau & snowmelt	Turc & snowmelt	Regression snowmelt
1965-66	A[a]	178	91	258	152
	H[b]	42	67	197	56
	L[c]	236	95	287	250
1966-67	A	149	46	175	127
	H	60	103	258	60
	L	253	156	374	250
1967-68	A	114	94	236	154
	H	52	37	127	53
	L	229	150	335	250
1968-69	A	138e	91	262	152
	H	74	34	140	53
	L	229	102	328	250
1969-70	A	162e	113	263	164
	H	36	37	118	53
	L	217	119	274	250

A - Athabasca H - Hay L - Liard e - estimate

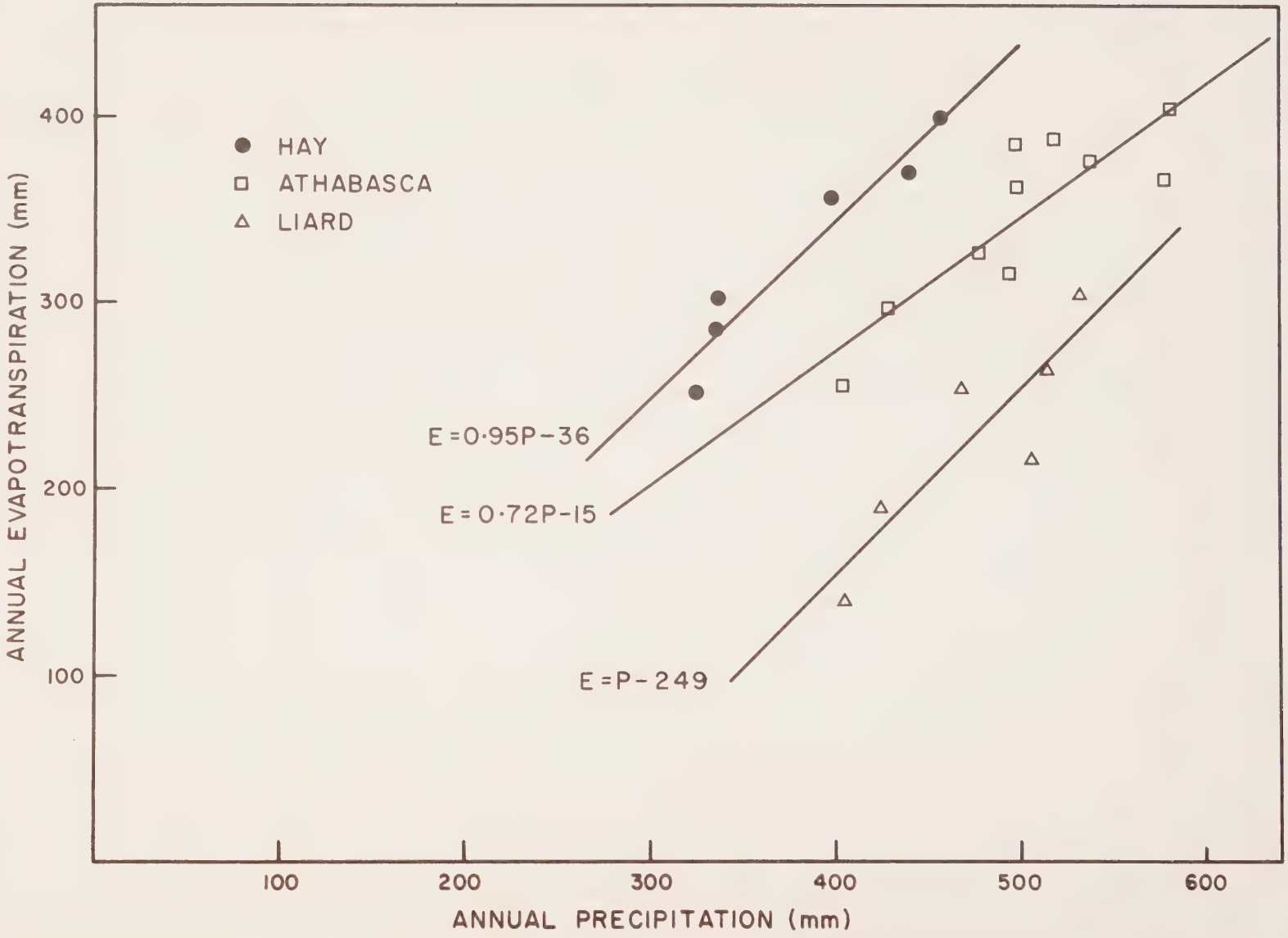


Figure 1. Plots of annual evapotranspiration versus annual precipitation for the Athabasca, Hay and Liard River basins, N.W.T.

SUMMARY AND CONCLUSIONS

All efforts have been spent so far in obtaining accurate estimates of the water balance components on an annual basis. Much more work will be necessary in order to achieve the same results on a month-to-month basis. This could involve experimentation with the input parameters and further alterations to the model itself.

So far, the model has been applied only to drainage basins for which runoff data exist. It is hoped that the model can be used to extend the data record on these basins and to synthesize it on others which have no data at all, such as the Hare Indian and Keele river basins. Data generated for these and other tributaries of the Mackenzie would be of importance to pipeline construction. The model would provide information on the average monthly discharges at river crossing locations. The data could also be used to assess the water supply of each major tributary, and the variation of this supply from season to season. This information would be useful during the construction phase and also later with the growth and development of settlements at river crossing sites.

ACKNOWLEDGEMENTS

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PRELIMINARY RESULTS FROM BOOT CREEK AND PETER LAKE WATERSHEDS, MACKENZIE DELTA REGION NORTHWEST TERRITORIES

by

J.C. Anderson and D.K. MacKay

Technical Report 2 to
Glaciology Division
Water Resources Branch
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ABSTRACT

Two small drainage basins, Peter Lake basin and Boot Creek basin, on the east side of the Mackenzie Delta, were selected for study as representative watersheds. In this study, emphasis is placed on the hydrology, and more specifically, the water balance of these two watersheds. Surficial geology, vegetation cover and permafrost features are also noted.

Methods and equipment used in the field are described. Data from two summers for Boot Creek basin and one summer for Peter Lake basin are analysed. Summer precipitation is observed to be light in total amount. Supporting data from the Inuvik airport suggest that monthly rainfall and snowfall amounts can vary greatly from year to year.

Most runoff occurs from late May until early October, peaking in the spring as snowmelt takes place. Direct runoff from three summer storms in Boot Creek basin is computed and found to be minimal. Runoff ratios for the same basin show considerable variation from month to month. The ratios for four months range between 5% and 57%.

Preliminary Results from Boot Creek and Peter Lake Watersheds, Mackenzie Delta Region, Northwest Territories*

by

J.C. Anderson and D.K. MacKay

INTRODUCTION

Two small drainage basins located on the east side of the Mackenzie Delta have been selected for study as research watersheds. One, Boot Creek basin, flows into the East Channel of the delta at Inuvik. The other, Peter Lake basin, is situated in the Caribou Hills just north of Reindeer Station. Its discharge flows northward into the Wolverine Lakes. The two watersheds are located within 55 km of each other and are of similar size. Peter Lake basin has an area of about 46 km^2, and the area of Boot Creek basin is 31 km^2 (Fig. 1). Both are in the continuous permafrost zone.

These basins have been chosen (for research) for a variety of reasons. Similar research has been undertaken in the eastern Arctic, especially at the McGill Sub-Arctic Research Laboratory near Knob Lake, Labrador. In the western sub-arctic, the University of Alberta has maintained an IHD representative basin, Baker Creek, near Yellowknife, Northwest Territories, for water balance and permafrost sudies. In Alaska, some watershed research has been done by Dingman (1966, 1971) and Slaughter (1971). (For the McGill research, the reader is referred to the 1966 publication of the Department of Geography, McGill University; for the University of Alberta research, see the Canadian Progress Report of the Secretariat, CNC/IHD).

When Boot Creek basin was proposed as a research basin in 1967, the Canadian Program for the International Hydrological Decade did not include plans for studies on watersheds in the western Arctic. On the basis of the lack of knowledge at the time on Arctic watersheds, establishment of this research basin was considered justified.

The proximity of the basin to Inuvik made the selection of Boot Creek logistically sound. Most of the basin could be reached from the town by snowmobile in winter and by foot in summer, if necessary. Also, the largest lake in the basin, Cynthia Lake, was big enough for landing a small plane (Fig. 2). The basin also offered a varied vegetation cover, due to its location on the tundra-taiga boundary.

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* The names "Boot Creek","Peter Lake" and "Cynthia Lake" are local names. They are not approved by the Canadian Permanent Committee on Geographical Names.

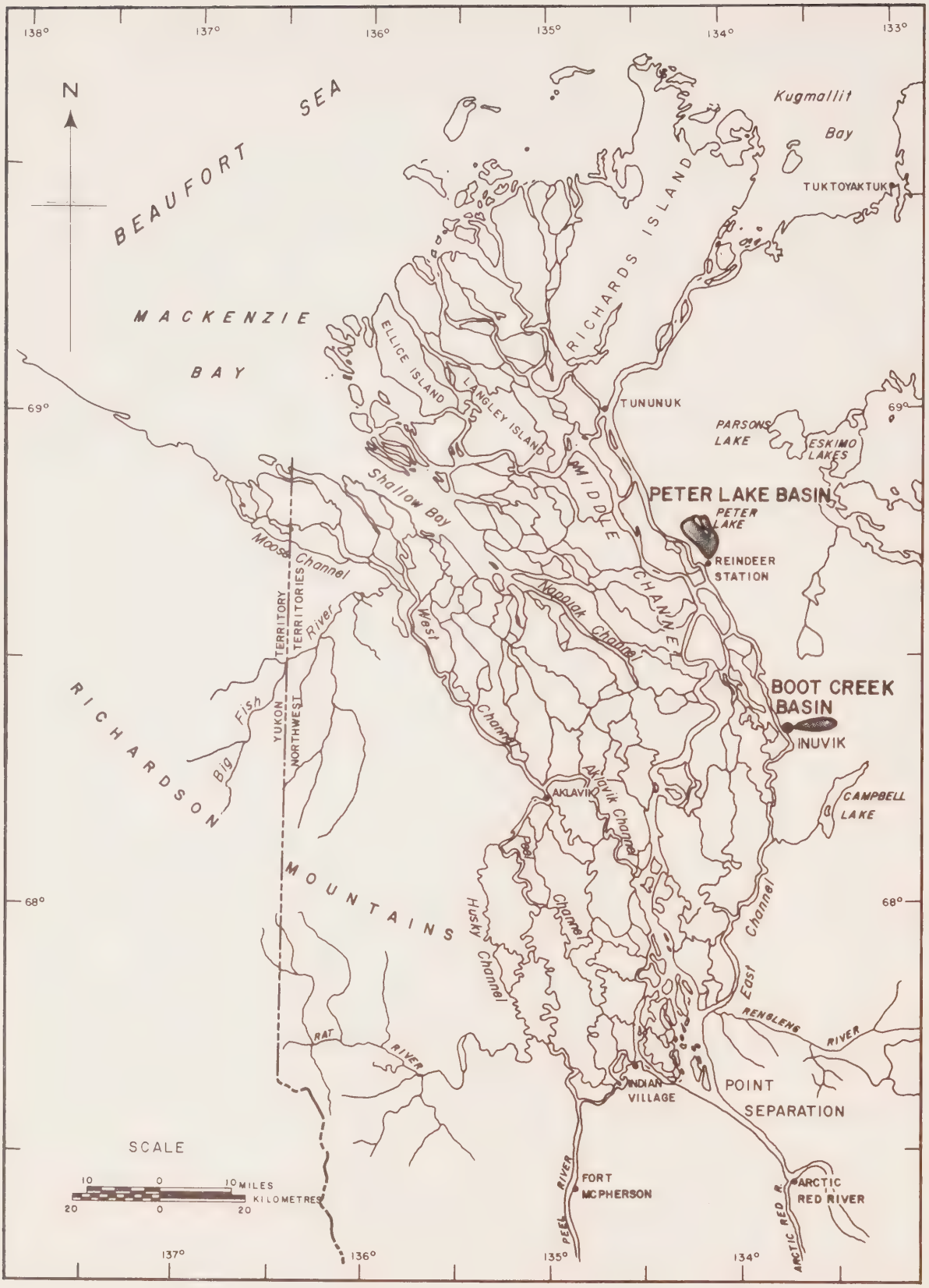


Figure 1. Location of Boot Creek and Peter Lake basins, N.W.T.

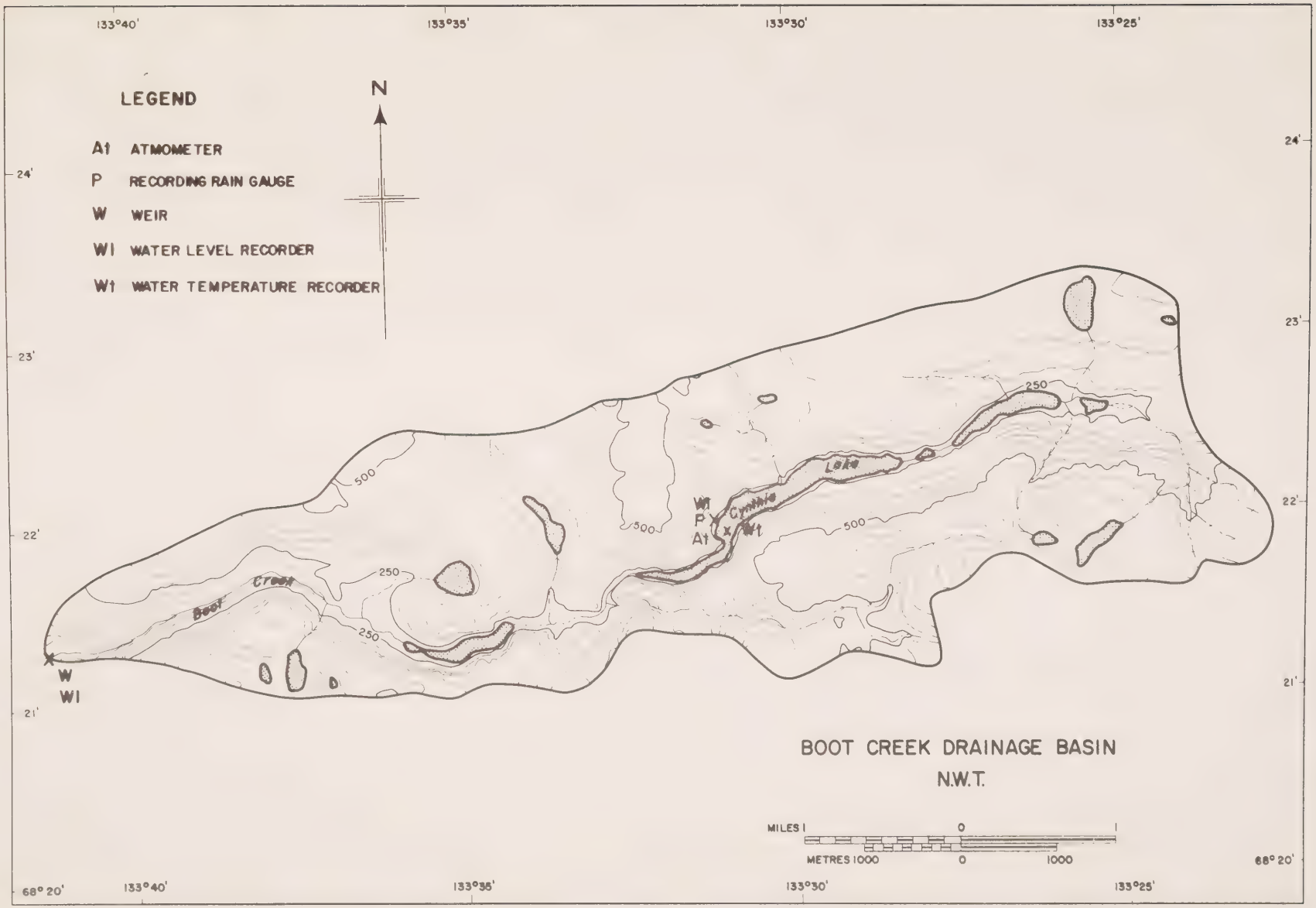


Figure 2. Lakes and instrument sites, Boot Creek basin, N.W.T.

Research began at Peter Lake in 1970 with the installation of ground-temperature probes in a variety of microrelief and vegetation-cover conditions. As no tundra basin existed which could be used for comparison with the Boot Creek taiga basin, a decision was made to measure components of the water balance at Peter Lake. The two basins are comparable in size, and Peter Lake basin is considered to be representative of the tundra environment in the Delta region.

Oil and gas discoveries have recently been made on Richards Island, on Tuk Peninsula, and at Parsons Lake, north and east of the two research basins. Oil and gas exploration is accelerating and, in fact, a drilling site is located less than one kilometre from the east shore of Peter Lake, well within the boundaries of its watershed. If sufficient discoveries are made in the delta region, large-diameter pipelines and associated gathering systems will link the reserves to southern markets. In such a case, these two research basins are strategically located for environmental impact studies.

The prime objective of this project was to study and compare the hydrology, especially the water balance, of the two basins. Permafrost phenomena are also a major point of interest. Boot Creek basin has undergone terrain disturbance due to natural causes such as a recent fire. Consequently, the basin provides opportunities for the observation of thermokarst processes in a taiga environment.

DESCRIPTION OF THE BASINS

Surficial Geology

There are no bedrock outcrops in either basin. Surface deposits in the Inuvik area consist of silt, clay and gravel, possibly of glacial origin. There are gravel deposits at the western end of Boot Creek basin which are being excavated for construction purposes.

Peter Lake basin is situated in the Caribou Hills. Here there are deposits of poorly consolidated silty clay and fine silt and sand. There are also outcrops of gravelly sand, particularly along the ridges at the north end of the basin.

Vegetation

From air photography and observations in the field, a vegetation map of Boot Creek basin was prepared (Fig. 3). The basin lies on the northern fringe of the taiga vegetation zone, and its cover may be termed forest tundra.

The vegetation is mixed taiga-lichen heath with fairly dense stands of spruce in the valley bottoms. Spruce tends to thin up the valley slopes and headward along the major stream to terminate near the hilltops. Intermingled with spruce are tamarack and stands of paper birch, the latter occurring mainly on west- and south-facing slopes of the western half of the basin, with black spruce on the opposite slopes. Hilltops and the upland

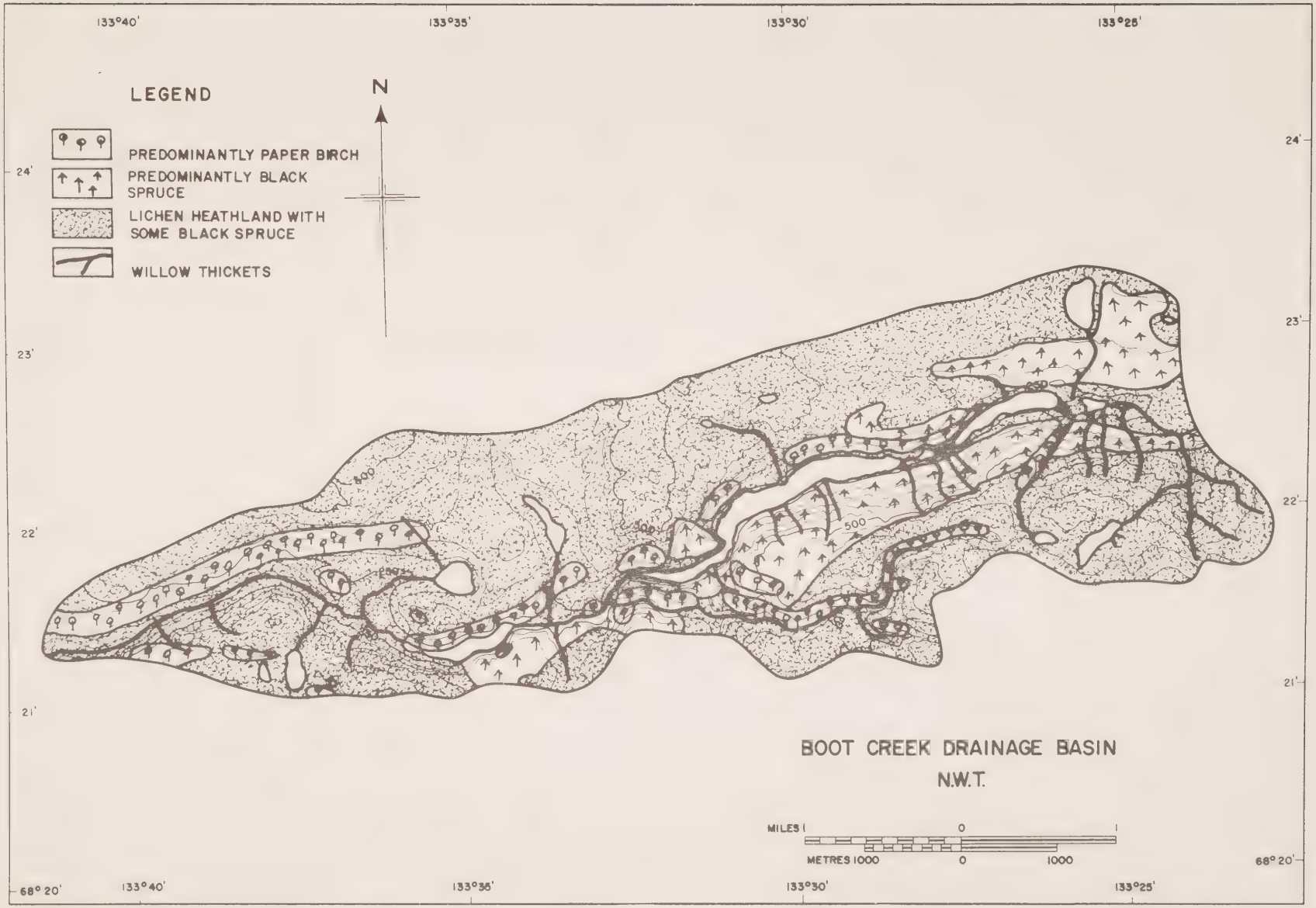


Figure 3. Vegetation cover of Boot Creek basin, N.W.T.

plateau region of the basin are characteristically lichen-heath land with ground birch, willow, and the occasional scrub spruce. Streams and rills are lined and often choked by dense willow growth.

During June and July of 1968, only 8 mm of precipitation fell, compared to a normal of 68 mm. As the surface vegetation and peat below it grew drier, the fire hazard became extremely great. Drought continued into August. On August 8, a fire broke out to the south of Boot Creek basin, and within a couple of days it had swept over more than half the basin (Fig. 4). Much of the vegetation just described was destroyed, and in its place a ground cover of fireweed and grass has sprung up.

At Peter Lake, with the exception of small alders and a few scattered spruce, trees are rare. Alders are found on hillsides, and also along watercourses. As in Boot Creek basin, the watercourses have a thick cover of willow, as well as ground birch and alder. Upland meadows are usually covered by ground birch and willow. In flat poorly-drained areas, mosses, sedges and lichens often form a thick carpet. On the slopes and hills surrounding Peter Lake, the surface is hummocky with an assortment of avens, lichens, cranberry and bearberry dominant on hummock crowns, with sedges, mosses, heather, willow and ground birch prevailing in the depressions. Photographs showing the vegetation as well as other aspects of the two basins are contained in the Appendix.

FIELD WORK

During the field season which runs from spring break-up in late May or early June until freeze-up in late September or early October, data are obtained for these basins. The Inuvik Research Laboratory serves as a focus for activities. From Inuvik, flights are made into the basins by float plane or helicopter. Boot Creek basin is also accessible by foot from Inuvik. At Cynthia Lake in Boot Creek basin, and at Peter Lake in Peter Lake basin, instruments are located so that they are easily accessible by float plane (Figs. 2 and 5). As soon as the lakes are free of ice, the instruments are flown in and set in operation. All instruments except the atmometers have recorders with charts that last a week or more. In this way, the instruments need only be checked once a week.

The number of instruments used has increased slowly since the project was started in 1967. During the 1972 field season, four M.S.C. tipping bucket rain gauges were installed, one at Cynthia Lake, one on the roof of the Inuvik Research Laboratory, and one at either end of Peter Lake. Stevens Type F water level recorders were used at the same two lakes, as were Ryan waterproof thermo-hygrographs (Model D). Where Boot Creek flows through a culvert beneath the airport road, another water level recorder was installed near a weir, to measure runoff. There was also a 250 cm^3 black porous disc atmometer at Cynthia Lake and Peter Lake.

A Lambrecht thermo-hygrograph was placed in a Stevenson screen at the south end of Peter Lake. For part of the 1972 season, a Moll-Gorczynski pyranometer (Kipp and Zonen) and a Lambrecht mechanical wind recorder were also in operation at Peter Lake. At the end of the field season, all instruments were removed and placed in storage.

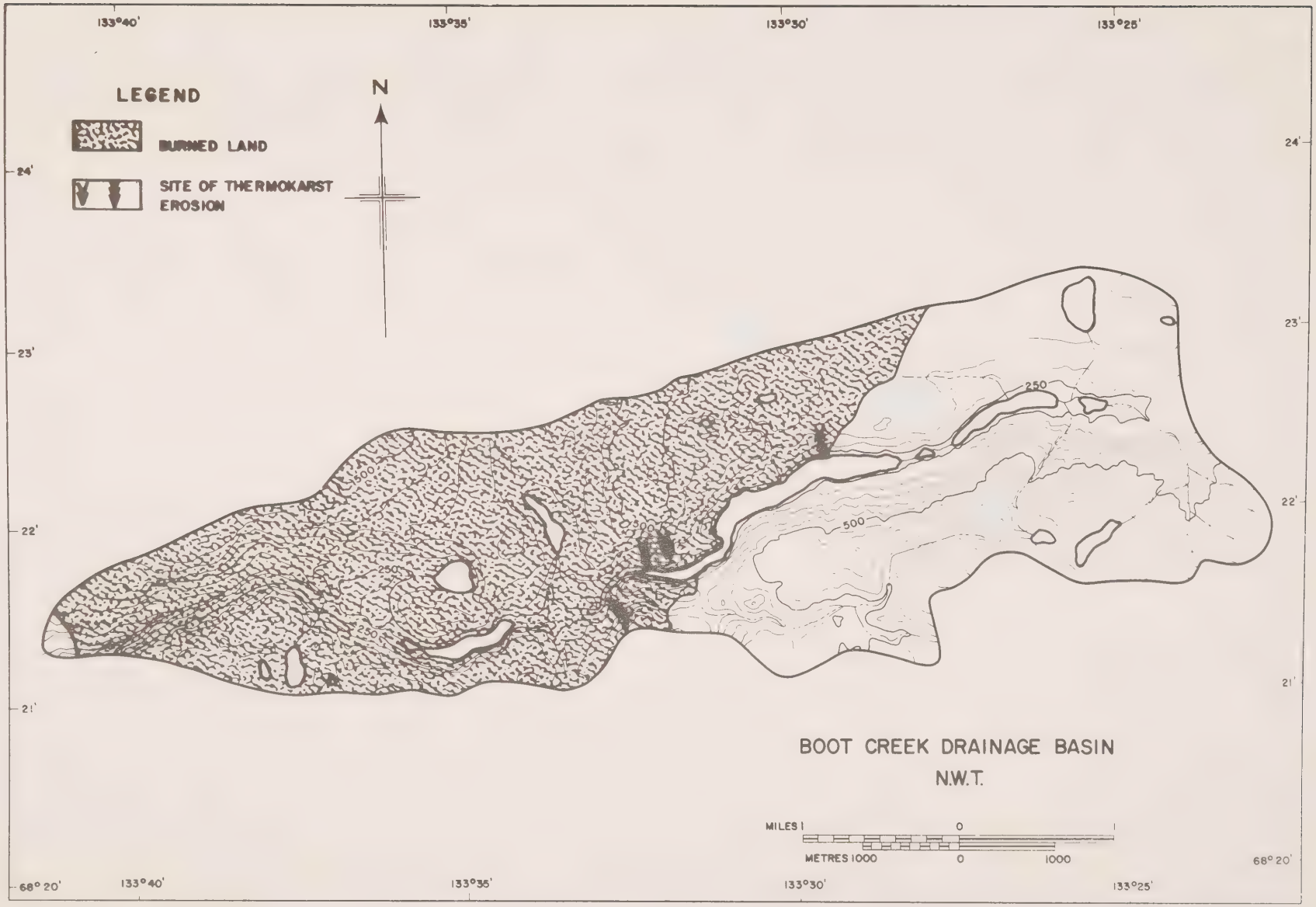


Figure 4. Extent of the 1968 fire, and sites of thermokarst erosion, Boot Creek basin, N.W.T.

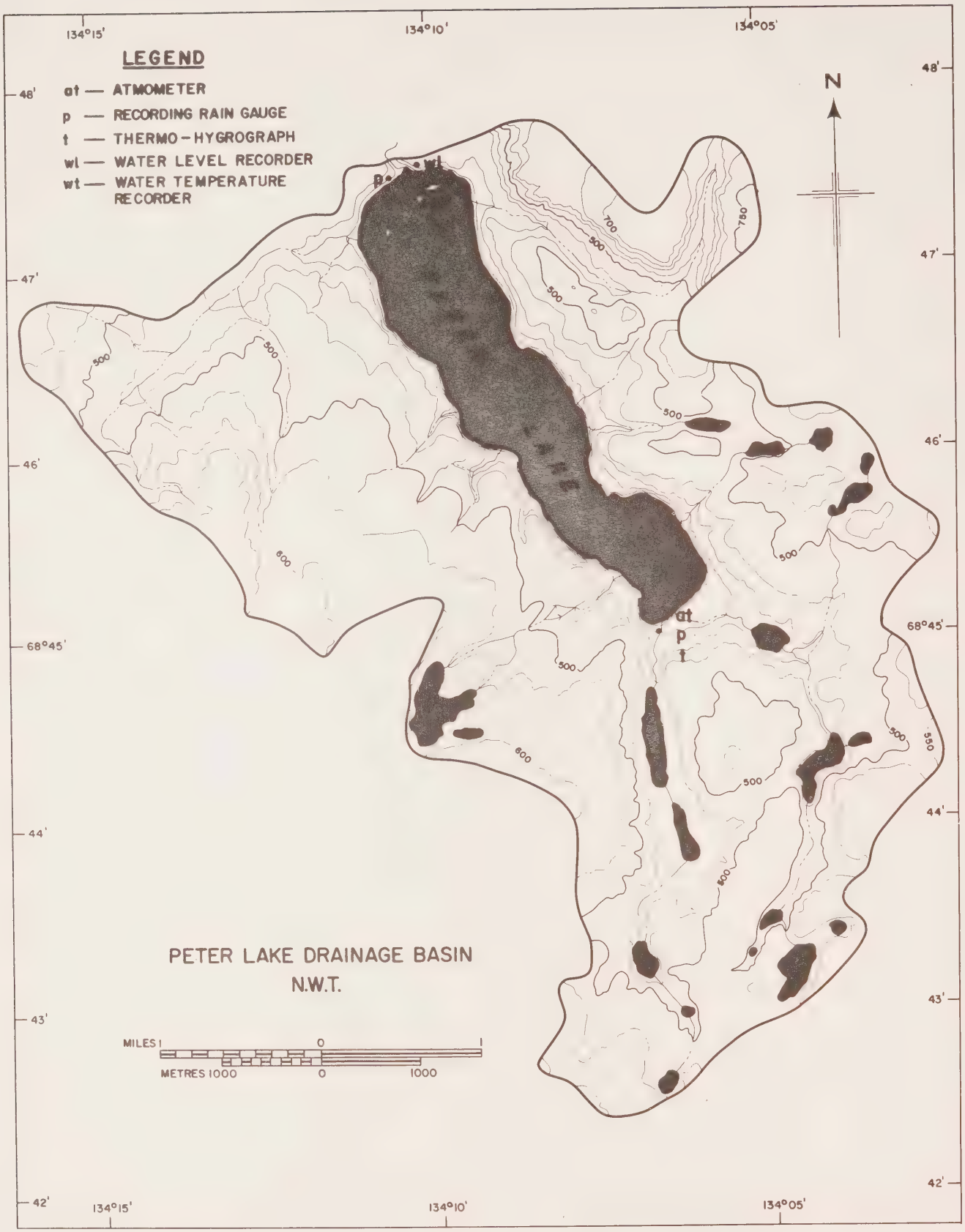


Figure 5. Lakes and instrument sites in Peter Lake basin, N.W.T.

Periodically during the 1972 field season, discharge measurements were taken at both basins, using both the Ott universal current meter (#C31) and a Pygmy current meter. These data were needed to establish stage-discharge relationships. The water level recorders were levelled with reference to a bench mark frozen into permafrost so that the same stage-discharge equations could be used in future years.

During the summer of 1967, the vegetation cover of Boot Creek basin was photographed from both ground and air. In the summer of 1972, black and white as well as colour air photo coverage was obtained for both basins.

RESULTS AND DISCUSSION

Most of the work of analysing the data was done after the 1972 field season, and this is still continuing. It is planned to place much of the data on computer punch cards for easier handling and analysis.

Precipitation

Two rain gauges were installed for each basin, at Boot Creek in 1971 and 1972, and at Peter Lake in 1972. In each case, a representative value for the amount of precipitation received was obtained by averaging the amounts collected in the two gauges. In 1970 and 1971, only one gauge was operating at Peter Lake. Monthly total precipitations for the basins are given in Table 1.

Table 1: Monthly precipitation totals: Inuvik airport, Boot Creek and Peter Lake.

Month	Precipitation (mm)						
	Inuvik Airport	Boot Creek		Inuvik Airport	Peter Lake		
	1971	1971	1972	Mean*	1970	1971	1972
June	6.6	7.9	44.3e	21.8			
July	24.6	26.7	11.8	46.0		35.3	4.1+
August	46.2	40.9	36.1	29.7	14.5	35.3	32.9
September	20.8	18.5	21.6**	17.8			15.9++
Total	98.2	94.0	113.8**	115.3			

* mean for the period 1957-1964

** to September 21 only

\+ from July 9 only

++ to September 24 only

e estimate

The Inuvik airport is located only 6 km to the south of Boot Creek basin. Precipitation totals are seen to be similar for the two locations in the summer of 1971. Thus for Boot Creek basin one can use airport mean values to represent mean values in the basin. On this basis the total precipitation for Boot Creek in 1971 was somewhat below normal, while in 1972 it was near normal.

July is usually the wettest month, but in 1971, July was very dry, as was June: and not until August did precipitation rise above normal. June 1972 was extremely wet, followed by a dry July and a wet August. Both Septembers were close to normal.

Not much can be said about the Peter Lake data because it is less complete and there is no meteorological station near enough for comparison purposes.

Runoff

Periodic flow measurements were taken at Peter Lake and Boot Creek in 1972 so that stage-discharge relationships could be developed. For the discharge at Boot Creek weir, the equation arrived at is:

$$Q = 3.35\ H^{2.36} \qquad (1)$$

where Q is discharge in cubic feet per second and H is the height of water at the weir in feet. Discharge values have been converted to metric units.

At Peter Lake, the entrance to the outlet stream at the north end of the lake acts as a natural weir. A value of 0.5 ft. (15.2 cm) was assigned to the lowest water level recorded on the lake during the 1972 season. Though arbitrary, this value was close enough to the actual depth so that a significant stage-discharge relationship was obtained. The discharge for Peter Lake equals

$$Q = 21.83\ H^{2.118} \qquad (2)$$

There was a weir at Boot Creek culvert in 1971, but it was destroyed by the spring flood in 1972 and had to be replaced. Since no discharge measurements were taken with a current meter in 1971, a stage-discharge relationship was not available for the original weir. However, both weirs were of the 90° V-notch variety and of similar construction, so the 1972 weir equation was considered accurate enough for the 1971 data.

Total flows on a weekly basis for Boot Creek and Peter Lake are listed in Table 2. Figures 6 and 7 present a comparison of runoff per unit area at Boot Creek in 1971 and 1972, and at Boot Creek and Peter Lake basins in 1972.

The eastern portion of the delta experienced record high discharge rates in the spring of 1972. In early June, the East Channel peaked - 23 ft above winter ice level, the highest value ever recorded for the East Channel. The discharge at Boot Creek peaked at about the same time, and as late as June 13, a flow of 1.7 m^3/sec was recorded, compared to 0.2m^3/sec a year earlier.

Although no continuous discharge records exist for Boot Creek in early June, it may be assumed that the discharge of 1972 was far greater than that of 1971. Perhaps the most important cause of the high runoff in 1972 was the heavy snowfall of the preceding winter. From October 1971 to May 1972, 276 cm of snow fell at the Inuvik airport; by comparison, only 169 cm fell between October 1970 and May 1971. Consequently, a lot of snow was available to melt in the spring of 1972, and to compound the high discharge from snowmelt, there was double the normal amount of rain in June (see Table 1).

Runoff declined through the summer at Boot Creek, reaching a minimum of 0.009 m^3/sec on August 2, 1972. There is a gap in the discharge record at this point, so the flow may have fallen even further through the first week of August. On July 22, 1971, a low flow of 0.003 m^3/sec was recorded.

Runoff ratios have been computed for Boot Creek basin, for individual storms as well as for longer time periods. In the analysis of storms, only direct or storm runoff was of concern, and base flow had to be separated from total runoff to obtain direct runoff. Base flow was defined as being constant

Table 2: Weekly discharge at Boot Creek and Peter Lake basins.

Time Span	Boot Creek Mean daily discharge (m^3/sec) 1971	1972	Boot Creek Total Discharge over basin (mm) 1971	1972	Peter Lake - 1972 Mean daily discharge (m^3/sec)	Peter Lake - 1972 Total discharge over the basin (mm)
June 24-30					1.36	17.98
July 1 - 7		0.17	0.43e	3.26	0.86*	6.52*
8 -14	0.015	0.10	0.28	1.93	0.61	9.20
15-21	0.010	0.05	0.19	0.90	0.48	6.32
22-31	0.011	0.02	0.30	0.60	0.30	5.66
Aug. 1 - 7	0.05		1.01		0.18	2.41
8 -14	0.10		1.89		0.16**	1.21**
15-21	0.12	0.04	2.37	0.84	0.14***	1.07***
22-31	0.26	0.12	7.23	3.42	0.14	2.63

* July 4 - 7 only

** August 8 - 11 only

*** August 18 - 21 only

e estimate

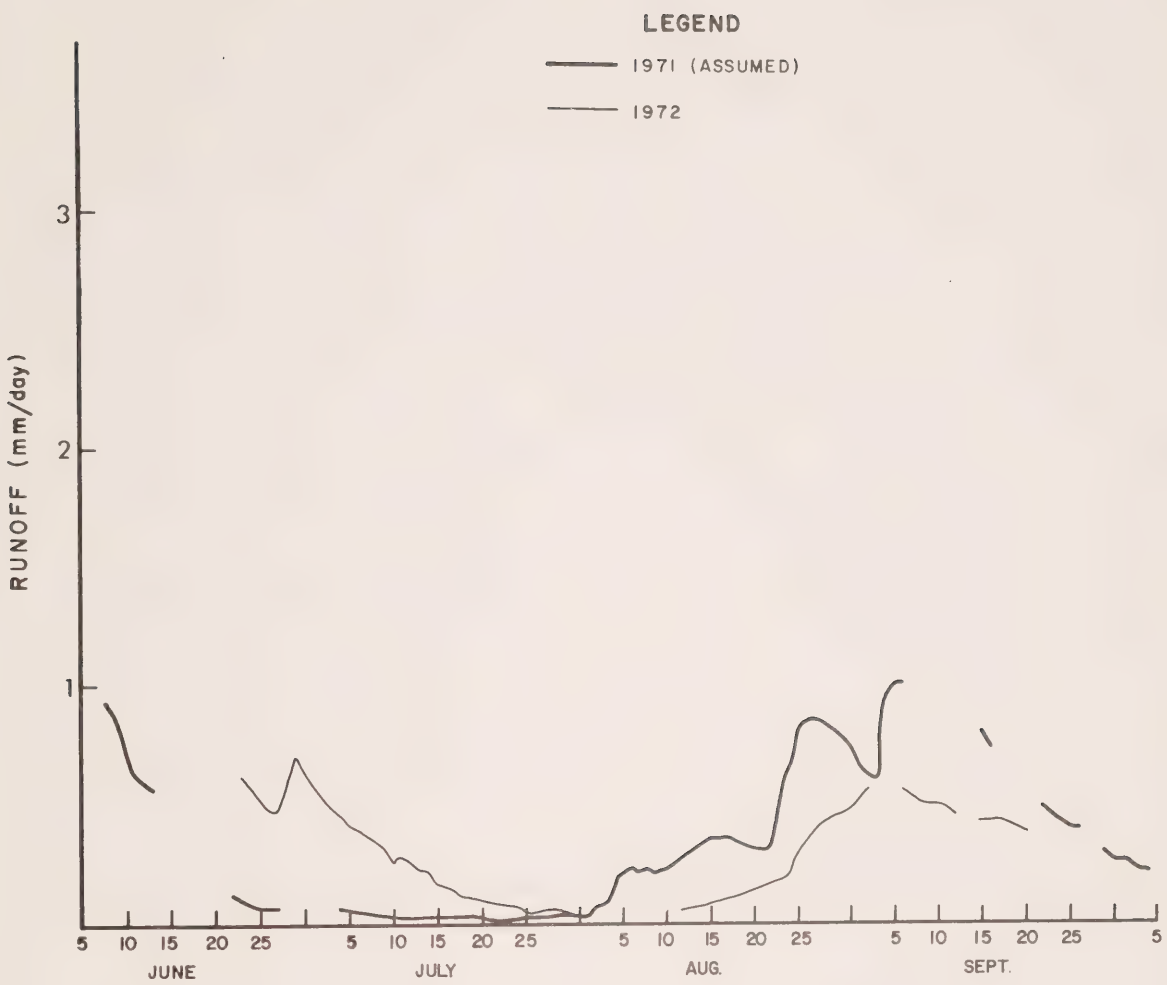


Figure 6. Total daily runoff for Boot Creek basin, 1971, and 1972, expressed as a depth of water per unit area.

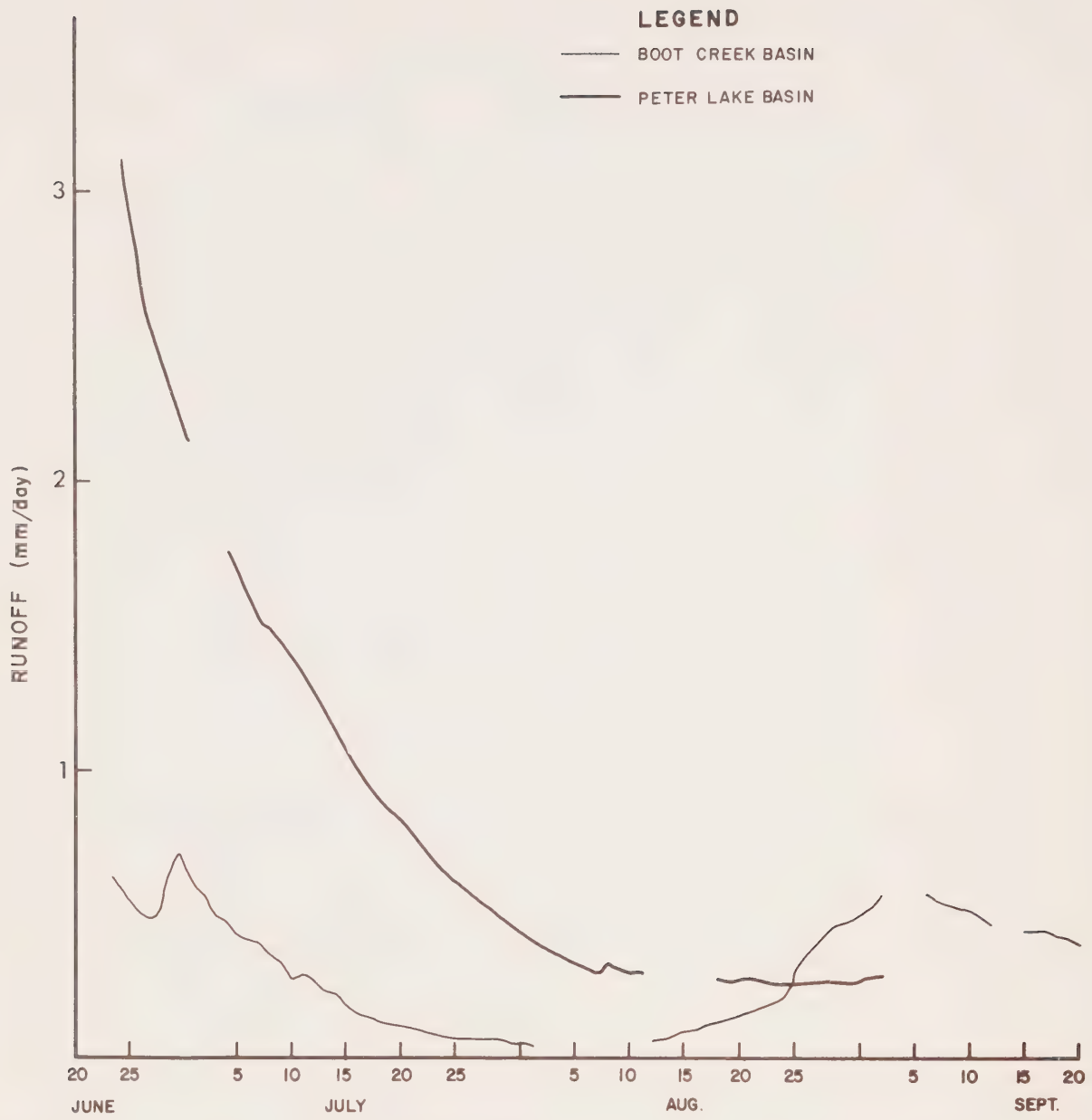


Figure 7. Total daily runoff for Boot Creek and Peter Lake basins, 1972, expressed as a depth of water per unit area.

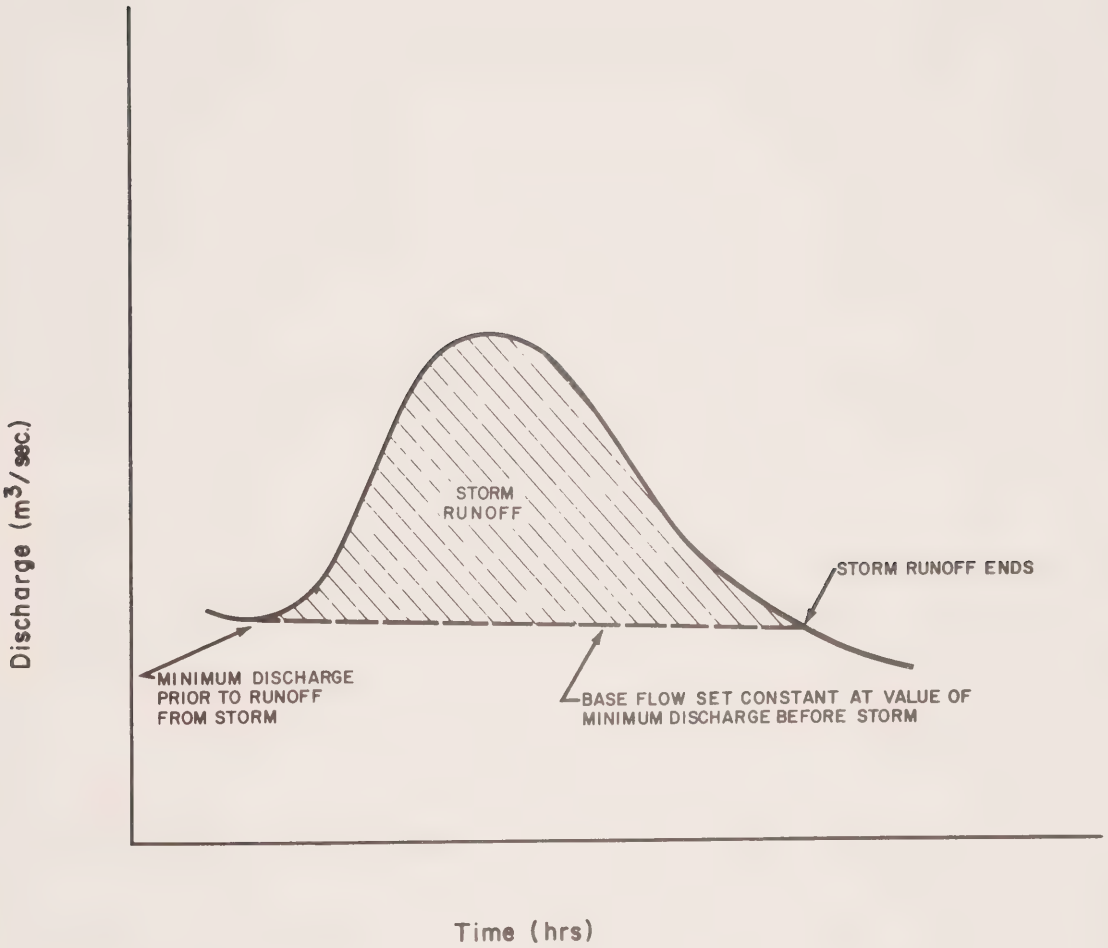


Figure 8. Method used to define storm runoff for three Boot Creek storm events in 1972.

at the minimum flow preceding the ascending limb of the storm hydrograph. Storm runoff was said to end when total runoff declined to the same level of base flow, as in Figure 8.

Table 3: Boot Creek discharge - storm runoff analysis.

Date of Storm (1972)	Rainfall (mm)	Storm Runoff (mm)	Runoff/Rain (%)
June 26-29	18.5	0.93	5
July 6	5.6	0.035	0.6
July 20	5.1	0.012	0.24

Direct runoff following a storm seems to be minor for these events. The runoff to rainfall ratio is highest for the storm in June because of the greater rainfall and because it comes most closely after the snowmelt period when the active layer is still very wet.

Much of the terrain is hummocky. The depresssions between hummocks could provide adequate storage for the rainfall and thus detain it. This may explain in part the low runoff ratios that have been found. Also, the water retention capacities of moss and peat are great, even in burned areas. Therefore, where this type of surface cover exists, direct runoff is probably close to zero.

Runoff ratios obtained by dividing precipitation into total runoff are given in Table 4.

Runoff ratios greater than 100% are possible for shorter intervals such as a week, owing to the delay time between rainfall and runoff. Much of the variation in the runoff ratios is due simply to the variation in rainfall from week to week. Monthly runoff ratios are all under 100%, but they still cover a broad range.

Through the course of a year, one would expect the high ratios of runoff to precipitation to occur during the snowmelt period. During the winter, runoff would decline to near zero, so that the runoff ratios in that season would be very small. Due to a lack of data, no annual runoff ratios are available.

An interesting feature of the 1972 Boot Creek hydrograph is the prolonged rise in discharge following major storms in August. Base flow was observed to increase in August of both 1971 and 1972. A possible cause for this could be the release of some depressional storage with increasing active layer thickness. Another contributing factor could be the melting of great amounts of ice contained in the soil near the permafrost boundary. Such melt would be accelerated by the release of latent heat from the rain. Figure 6 shows that flow continues to increase following the storms of August 10 to 13 (9.7 mm) and August 25 to 26 (9.8 mm) in 1972.

Table 4. Total runoff, precipitation, and runoff ratios for Boot Creek basin.

Time Span	Runoff (mm) 1971	Runoff (mm) 1972	Precipitation (mm) 1971	Precipitation (mm) 1972	Runoff Ratio (%) 1971	Runoff Ratio (%) 1972
July 1-7	0.43e	3.26	0.00	5.84	-	56
8-14	0.28	1.93	7.24	0.25	4	772
15-21	0.19	0.90	5.46	5.46	4	17
22-31	0.30	0.60	13.97	0.25	2	240
Aug 1-7	1.01	m	21.96	2.41	5	m
8-14	1.89	m	10.03	12.57	19	m
15-21	2.37	0.84	0.73	5.97	325	14
22-31	7.23	3.42	8.13	15.11	89	23
July	1.20	6.69	26.67	11.80	5	57
August	12.50	4.26*	40.88	{ 36.06 / 21.08* }	31	20*

e - estimate
m - data missing
* - August 15 to 31 only

Runoff per unit area at Peter Lake basin is greater than at Boot Creek basin until August 25 of the 1972 season (Fig. 7). Because of its size, Peter Lake acts as a reservoir, storing some spring snowmelt for release later in the season. Also, the spring runoff peak at Peter Lake is later, due to the higher elevation and more northerly latitude of the basin. Ice was still seen on the lake on July 3, 1972, and some snowbanks persisted through July 21. In 1972, total runoff for the two periods of July 1 to 31 and August 15 to 31 amounted to 31.4 mm at Peter Lake basin compared to only 10.0 mm at Boot Creek basin.

Runoff ratios for Peter Lake basin are given in Table 5. Weekly values in August show very little variation, primarily because of the even distribution of rainfall throughout the month. Again, due to a lack of data, no annual ratios are available and consequently long-run runoff ratios remain unknown.

Evapotranspiration

A 250 cm^3 atmometer was located in each basin in 1972, and during the sunny weather of July the total volume of water would evaporate within a week. Evaporation declined in August as cloudy wet weather became more predominant.

Atmometer readings are useful only as a relative indicator of a change in the evaporation rate from week to week. Evapotranspiration from the land surface remains unknown. However, Bliss (1972) has suggested that evapotranspiration from a lichen cover may be greater than that from flowering plants. He also claims that mosses and lichens offer little resistance to water loss. As these cover types are abundant in both basins, one would

Table 5. Total runoff, precipitation, and runoff ratios for Peter Lake basin, 1972.

Time Span	Runoff (mm)	Precipitation (mm)	Runoff Ratio (%)
July 15-21	6.268	1.524	411
22-31	5.609	0.508	1104
Aug 1-7	2.388	8.382	29
8-14	2.048e	8.509	24e
15-21	1.881e	8.128	23e
22-31	2.609	7.874	33
August	8.926e	32.893	27e

expect high rates of evapotranspiration during sunny weather, when water was available.

Soil Moisture

Soil moisture probes were installed at Peter Lake basin in 1972. Upon their removal in late August, soil samples were taken to determine the percentage water content of the material surrounding each probe. In a mossy site, these values ranged between 700% and 1365% (percentage water with respect to dry weight). At another site in peat which had a cover of moss and grass, the values were from 475% to 635%. The samples were taken following a few days of light rain, but they illustrate a point mentioned earlier, namely that peat and moss have a very high water retention capacity.

Permafrost Phenomena

A traverse was made near the west end of Boot Creek basin on August 15, 1972 to determine active layer depths. The surface cover along this traverse had been burned in 1968. Since then grasses and fireweed were the most abundant vegetation types there.

On the north-facing slope, the active layer was deepest beneath exposed charred hummocks (up to 75 cm), due to their low albedo. Beneath grass and fireweed the active layer was 30 to 45 cm deep, but under charred moss, it was only 25 cm deep. Even though the moss was dead, it offered good insulation to the permafrost below.

On the south-facing slope, the active layer was deeper as the insolation was much greater. On the steeper part of the slope, the active layer was over 60 cm deep, and it often exceeded 100 cm. Where the slope was more gentle near Boot Creek, the active layer was 30 to 70 cm deep, and shallowest again under burned moss.

Following the 1968 fire, zones of thermokarst erosion developed, mainly near Cynthia Lake. Figure 4 shows the more important thermokarst erosion sites. Gullying has occurred at most of these locations.

Since the fire of 1968, J.A. Heginbottom (1972) has studied active layer thickness and earthflows near Inuvik. Just south of Boot Creek basin, he found that by July 1970, the median depth of active layer was 9 cm greater along a burned line of study, as compared to a nearby unburned line. Also, along the burned portion of Boot Creek Valley, seventeen earthflows were noted as occurring between May 22 and August 9, 1969.

Polygons are common at Peter Lake in low, ill-drained areas of gentle slope. They are all of the high-centered variety. Boot Creek basin has a major field of polygons at its northeast corner, and these are also high-centered.

In an area of polygonal ground at the north end of Peter Lake basin, vegetation was removed to expose two ice wedges intersecting at right angles. Above the ice there was a cover of moss, while away from the wedge the vegetation cover was more varied and included lichens, mosses, dwarf birch and some tundra flowers such as cloudberry.

CONCLUSIONS

Precipitation in Boot Creek and Peter Lake basins is light and variable. Sever drought conditions can develop, as in 1968. Although the permafrost is only a foot or two below the surface, the vegetation mat can become dry from the lack of rain, and susceptible to fire.

Most runoff occurs from late May until early October, and peak runoff occurs with the spring snowmelt in late May or early June at Boot Creek. The peak is somewhat later at Peter Lake. At Boot Creek, discharge usually declines through July and can rise to high values again in August. Aside from the precipitation which falls on the lakes of Boot Creek basin, there is little direct runoff following summer storms. Most of the rain is held in depression storage and in the peat of the active layer.

Runoff ratios for weekly and monthly periods have been presented for both basins. The ratios vary considerably, especially from week to week. Unfortunately, annual ratios cannot be derived from the limited data at hand.

Evapotranspiration remains an unknown quantity, but it is probably very high when conditions are favourable.

Soil moisture content can be extremely high because the permafrost table obstructs the percolation of precipitation. Mosses and peat in particular are capable of holding large amounts of water.

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Photograph 1. Boot Creek during the spring runoff peak, June 4, 1972. Note the growth of spruce and willow along the banks of the channel.



Photograph 2. Boot Creek culvert, June 3, 1972, during the spring flood. Only after the water level fell could a weir and water level recorder be installed to measure runoff. The culvert is eight feet in diameter.



Photograph 3. Installation of water level recorder at Boot Creek culvert, June 1972. The weir can be seen extending across the face of the culvert.



Photograph 4. Before it melts, ice is another obstacle to streamflow measurement at Boot Creek culvert in the sprin



Photograph 5. Lower Boot Creek basin, summer 1967. The south-facing slope in the foreground supports birch and willow trees. The north-facing slope across Boot Creek has a less dense growth of black spruce.



Photograph 6. Black spruce in Boot Creek valley, summer 1967.



Photograph 7. Looking east towards the first lake as one heads upstream on Boot Creek. Note the denser birch forest on the south-facing (left) slope.



Photograph 8. View from the north across the lower portion of Boot Creek valley. Note the spruce trees and dense willow which obscure Boot Creek from sight in the valley bottom.



Photograph 9. West half of Cynthia Lake, looking south. Instruments were located in and near the bay marked by an arrow. (See also Figure 2.)



Photograph 10. Near eastern end of Boot Creek basin, looking north. An area of polygons in the upper centre obtains its light colour from a dense cover of lichens.



Photograph 11. Boot Creek valley as it appears in winter, looking west across the last lake in the chain heading downstream along Boot Creek.



Photograph 12. A hillside in Boot Creek basin after the 1968 fire. Surface cover has been stripped from the tops of hummocks (grey areas). The charred remains of dwarf willow trees are visible between hummocks. The picture was taken in spring 1972, prior to the regrowth of grasses and fireweed.



Photograph 13. View of Cynthia Lake, looking east, July 1972. Some results of the 1968 fire can be seen, such as the thermokarst erosion on the slope at centre left. Unburned land is seen in the background. The purple flower is fireweed.



Photograph 14. At Cynthia Lake, September 1970. Fire burned the north (right) shore, but not that part of the south shore visible on the left.



Photograph 15. Stevenson screen and recording rain gauge (in front of instrument shed) at south end of Peter Lake. Note the tundra vegetation. Labrador Tea is in bloom in the foreground.



Photograph 16. Outlet stream and gravel ridges at north end of Peter Lake.



Photograph 17. Looking towards the water level recorder from the outlet stream at Peter Lake.



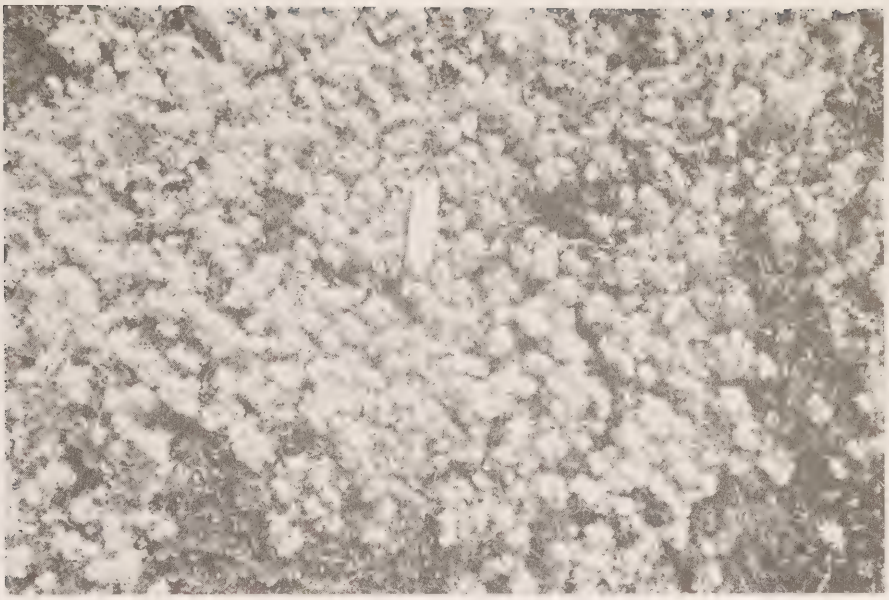
Photograph 18. Discharge measurement section, outlet stream at Peter Lake. Ties on the string are one foot apart.



Photograph 19. A section of the outlet stream, Peter Lake, showing beaded character of the channel. Some alder and willow are visible along the channel banks. They are accompanied by ground birch on portions of the valley slopes.



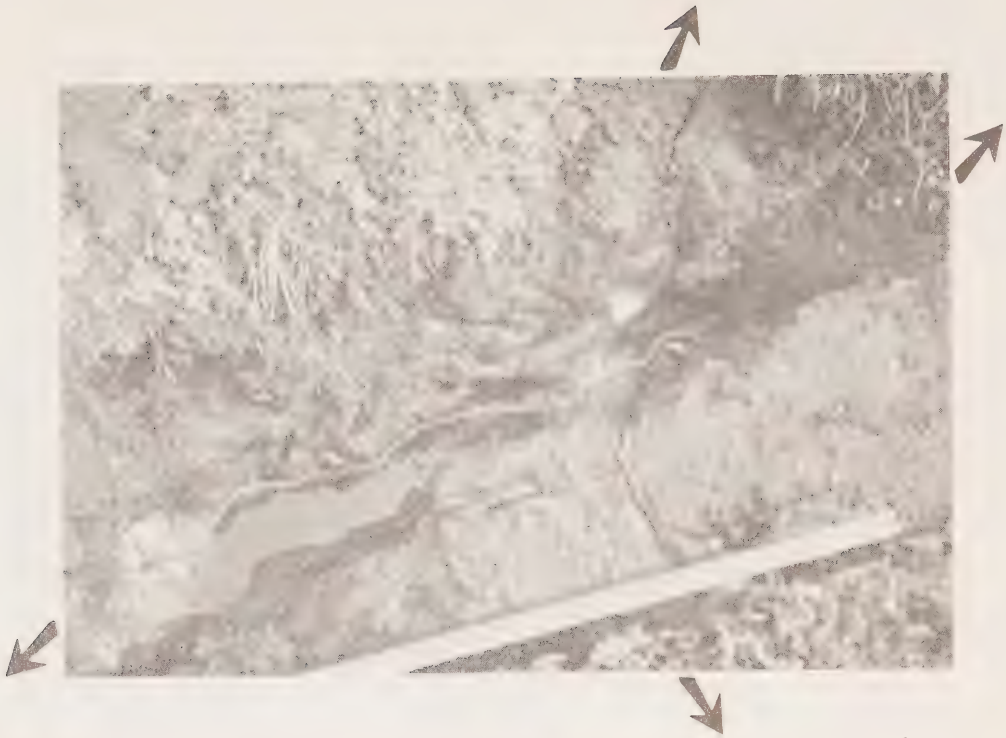
Photograph 20. Moss hummock, about 1.5 m in diameter, at north end of Peter Lake basin. A Moll-Gorczynski pyranometer is seen in the background.



Photograph 21. Reindeer moss (a lichen), Peter Lake basin. The can opener is about 10 cm long.



Photograph 22. Ground birch, Peter Lake basin. The can opener is about 10 cm long.



Photograph 23. Ice wedges at Peter Lake basin. The surface cover was removed to expose two intersecting wedges, as indicated by arrows. Meltwater covers some ice at the bottom of the trough.



Photograph 24. Two soil profiles obtained while cutting across ice wedge in Photograph 23. Moss on the right covered the ice wedges. Elsewhere, soil was peaty like that on the left. A metric tape is shown for scale (divisions in cm).

Preliminary Study
of the
SEASONAL DISTRIBUTION OF FLOW
IN THE
MACKENZIE DELTA, NORTHWEST TERRITORIES

by

R. J. Anderson and D. K. MacKay

Technical Report 3 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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ABSTRACT

In recent years, the Mackenzie Delta has become an important petroleum exploration area. Historically, the delta is a significant trapping area and, moreover, a wildfowl breeding region. For these reasons, it was considered desirable to initiate a study of its hydrologic behavior beginning with a detailed analysis of the delta streamflow distribution.

Runoff from a basin area of 1,801,600 km^2 passes into the delta and on to the Beaufort Sea. Flow is through a channel and lake maze which empties into the sea at many locations along the outer delta perimeter. Within the maze, delta stations have been located on major channels in order to examine the regional character of streamflow. Measurements at these stations have been made by Glaciology Division in the summer months of 1971, and by Glaciology and Water Survey of Canada Divisions in March, 1972.

Channel parameters consisting of cross-sectional area, width, mean velocity and mean depth are studied in relation to discharge. The resulting four hydraulic geometry equations represent an average interrelationship among these factors during a mid-summer period in the delta. Cross-sectional area and width can be used to calculate discharge from the hydraulic geometry equations only for relatively low summer stages.

A detailed March distribution study is presented as are trends in delta ice thicknesses. The study shows that 78 percent of delta inflow remained in Middle Channel as far north as Langley Island near Tununuk Point. Ice thicknesses greatly alter the flow distribution pattern over the winter season. Ice thicknesses in the Delta increased latitudinally despite the fact that snowfall distribution was somewhat different than during past winters.

INTRODUCTION

Nature and Scope

The Mackenzie River is the longest in Canada and one of the ten longest rivers in the world. Numerous tributaries collect runoff and sediment from a basin of 1,801,600 km^2 to form the Mackenzie River system. The runoff from this vast basin passes through the many channels of the Mackenzie Delta to the Beaufort Sea. The discharge of the Mackenzie River at Norman Wells may exceed 14,000 m^3/sec during the summer months (June and July), with a peak of over 19,500 m^3/sec at break-up in late May or early June. Late winter discharges may be below 2,800 m^3/sec while mean annual discharge is estimated at 8,500 m^3/sec. It should be noted that the flow of the Mackenzie where it empties into the delta at Point Separation will be considerably greater than that indicated at Norman Wells.

A detailed study of the physical geography of the delta was made by J.R. Mackay (1963). Henoch (1960) examined some of the geomorphic aspects of the southern delta area. This paper describes the seasonal distribution of flow in delta channels during 1971-72 and some factors which affect the winter flow network. The streamflow data were obtained at sites located on major delta channels (Figs. 1 and 2). A list of these stations is contained in Appendix I.

Objectives

The objectives of this research report are:

(1) To study the discharge and seasonal distribution of flow through the Mackenzie Delta, N.W.T.

(2) To develop a set of hydraulic geometry equations to describe the flow response in delta channels based on available open water data.

(3) To measure variations in water levels, ice levels and ice thicknesses on major delta channels.

(4) To examine and explain the causes of flooding in the delta.

Relation to Pipeline Development

During pipeline construction, the major delta channels will form part of the necessary transportation network for moving supplies and equipment. As channels are used in winter as roads and air strips, a knowledge of ice thicknesses, ice levels and overflow onto ice surfaces is important. The effects of channel ice blockages on flooding in the delta at break-up is also an important factor in the location of supply depots and docking facilities as well as in determining the elevation to which gravel pads must be built at drilling sites. In addition, a knowledge of the flow pattern under delta ice conditions is required in the event that pollutants enter streamflow at any point above or within the delta.



Figure 1. Discharge measurement stations, nos. 1-25 and cross-sectional analysis of flow distribution, Mackenzie Delta.

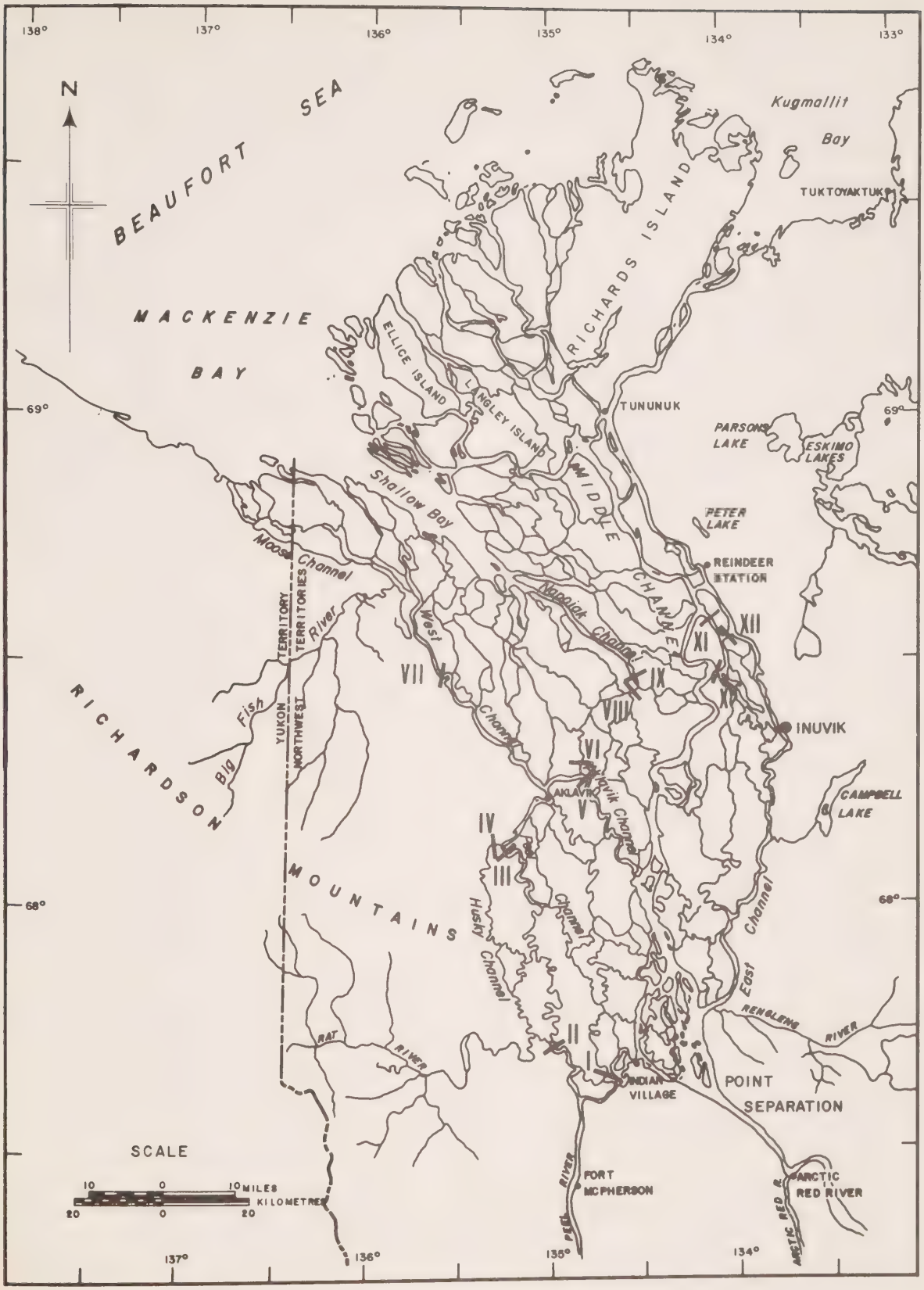


Figure 2. Miscellaneous discharge measurement sites, 1-X11, summer 1971, Mackenzie Delta.

METHODS AND SOURCES OF DATA

As shown in Figure 1, the delta was split into a number of sections in order to simplify the problems associated with flow distribution analysis. Flows from the Rat, Big Fish and Rengleng Rivers have been neglected as not significant to this study. Table 1 summarizes the flow through each section.

Field Techniques

Summer

During the summer months of 1971, reference benchmarks were established at each of the sites listed in Tables 2 and 3 and water levels, bottom profiles, channel widths, surface water (1.0 m) temperatures and current velocities were measured. Current velocities were taken at 0.2 and 0.8 of the depth below the surface at each point in a cross-section. Middle Channel measurements, however, could not be made with the equipment available in 1971 and discharge measurements could not be completed at B (7 + 8) in the time available. As a result, only one incomplete set of summer flow measurements is available for analysis. In 1971, delta discharge measurements were made only south of 68°35'N.

Winter

Discharges were measured in March 1972 by two crews employing a fixed-wing aircraft and a snowmobile. A number of measuring holes were drilled at equal intervals at each channel cross-section with a power auger. Water levels at each station were referenced to benchmarks. Depths, water level with respect to the bottom of the ice sheet, hole spacings and velocities at 0.2 and 0.8 of the measured depth below the water surface were measured for all stations. In addition, overflow, amount of snow cover and wind direction were noted.

Two different methods of current measurement were used. In channels where depths were less than 9 m, velocity was measured with a current meter mounted on a rod. In deeper channels, a current meter - lead weight assembly on a cable was necessary. For the latter, a heated chamber mounted on skis was used to prevent the cable, winch and current meter from freezing (Strilaeff and Wedel, 1970).

At Stations 1 and 2 (Fig. 2), on the Peel River and Arctic Red River respectively, automatic water-level recorders were installed at least two years ago. A new site on the Mackenzie River, Station 3, complete with automatic recorder, was set in operation in 1972. In the future, Stations A, B, C, 16 and 11 (Fig. 1) will have automatic recorders installed for flow-distribution purposes.

Data Analysis

Discharge calculations were made using standard procedures. Data collection and original calculations were made in British units and the results converted to metric units.

Table 1. Distribution of flow in the Mackenzie Delta into sections (refer to Figure 1).

	Stations
Flow to Delta - Section U-U	= 1 + 2 + 3
Flow at station A	= 1 - 4 - 5 - 6
Flow in Middle Channel at v_1	= A + 2 + 3 - 7 - 8
Flow across Section V-V	= 4 + 5 + 6 + v_1 + 7 + 8
Flow at w_1	= 9 + 10 + 12 - 11
Flow across Section W-W	= 11 + w_1 + 16 + 17 + 18
Flow at x_1	= 11 - 13 - 14 - 15
Flow across Section X-X	= w_1 + 13 + 14 + 15 + x_1
Flow at y_1	= 16 + 17 + 18 + 19 - 20 - 21
Flow across Section Y-Y	= 19 + y_1 + 20 + 21
Flow at z_1	= 20 + 21 - 22 - 23 - 24 - 25
Flow across Section Z-Z	= 23 + 24 + 25 + z_1

Mean depth is expressed as D = A/W in meters. Mean velocity is expressed as V = Q/A in meters/sec. Mean ice thickness is the depth of ice remaining below water level and actually represents a minimum ice thickness except where overflow occurs. Stage measurements at different sites cannot be compared because there is no common datum.

The relations between discharge and channel width, mean depth, and mean velocity can be represented by three hydraulic geometry equations suggested by Leopold and Maddock (1953). The equations are:

$$W = aQ^b \quad (1)$$

$$D = cQ^f \quad (2)$$

$$V = kQ^m \quad (3)$$

In these equations W = width, D = mean depth, V = mean velocity, Q = discharge, a, c and k are coefficients and b, f and m are exponents. It is known that Q = AV where A is the cross-sectional area and also that A = WD. Therefore, A can be written as:

$$A = acQ^{b+f} = jQ^n \quad (4)$$

Because Q = WDV and, thus, $Q = ackQ^{b+f+m}$, the sum of the exponents b+f+m = 1.0 and the multiplication of the coefficients must be a x c x k = 1.0. When plotted on log-log paper, Equations 1 to 4 represent straight lines.

Both at a given station and in a downstream area, width, depth and velocity increase with discharge. The coefficients and exponents will vary from station to station but an average value can be computed. These equations are applicable only during the low summer water season.

In order to calculate the average values of the coefficients and exponents in Equations 1 to 4, it is necessary to complete a linear regression analysis of channel parameters versus discharge; then the regression lines representing these equations can be plotted.

RESULTS

A tabulation of all available streamflow data is made in Appendix II, Tables 2 to 5. In Table 6, hydraulic geometry equations and their linear correlation coefficients are shown. Exponents representing the slopes of the regression lines and the coefficients representing channel parameters of area, width, mean velocity and mean depth at unit discharge are also listed in Table 6. Plots of discharge versus area, width, mean depth and mean velocity are shown in Figures 3 to 6. The regression lines of A, W, D and V on Q have been plotted. Analysis of the winter data yields results shown in Table 7.

TABLE 6

Hydraulic Geometry Equations For

Mackenzie Delta Channels

Hydraulic Geometry Equations

	Equations	Coefficients of Correlation
(5)	$A = 13.6\ Q^{.731}$	.918
(6)	$W = 8.47\ Q^{.554}$	.919
(7)	$V = 0.075\ Q^{.269}$	.651
(8)	$D = 1.63\ Q^{.174}$	.545

Coefficients Representing Slopes of Regression Lines

Width	Depth	Velocity	Area
'b'	'f'	'm'	'b+f = n'
.554	.174	.269	.731

Exponents Representing Characteristics at Unit Discharge

Width	Depth	Velocity	Area
'a'	'c'	'k'	'axc = j'
8.47	1.63	.075	13.6

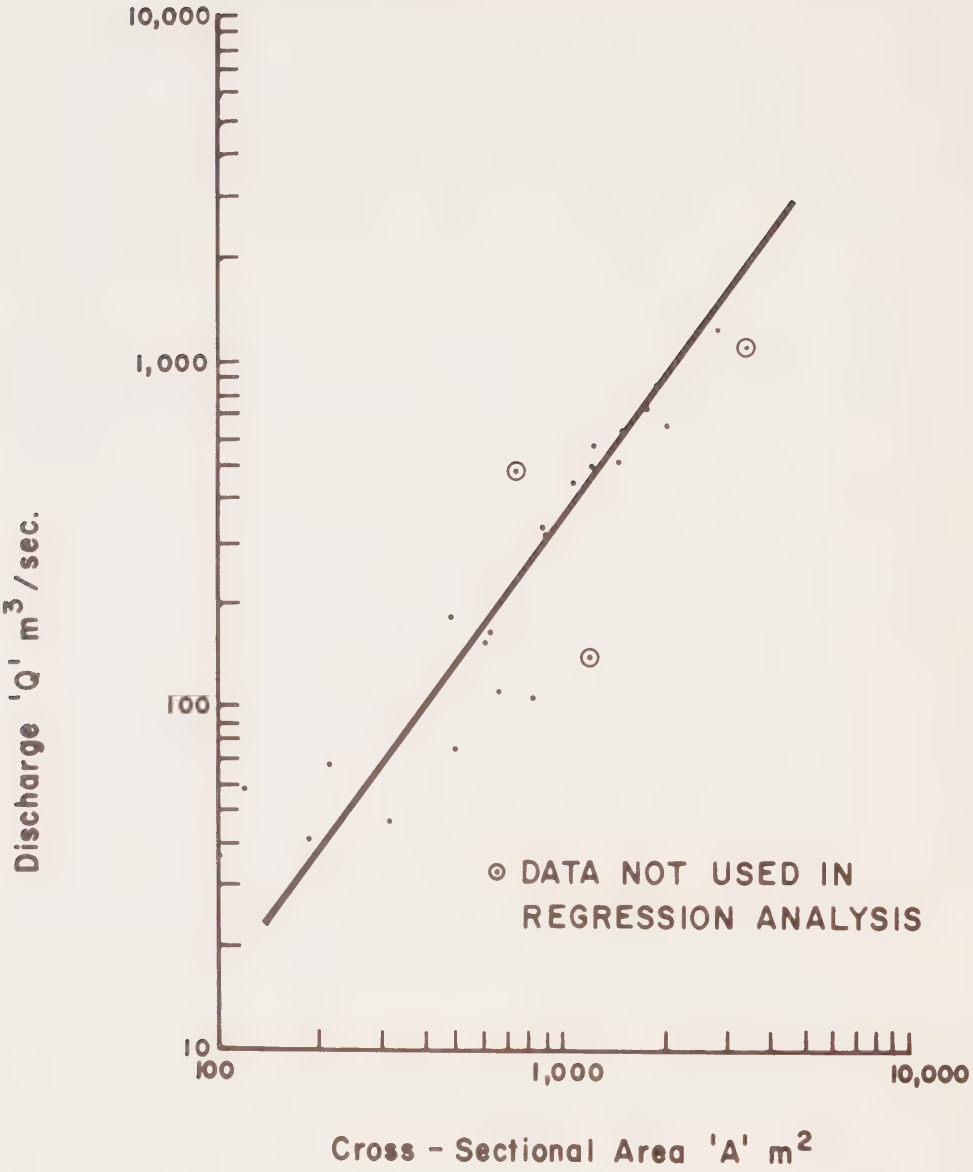


Figure 3. Plot of discharge versus cross-sectional area for delta channels, Mackenzie Delta.

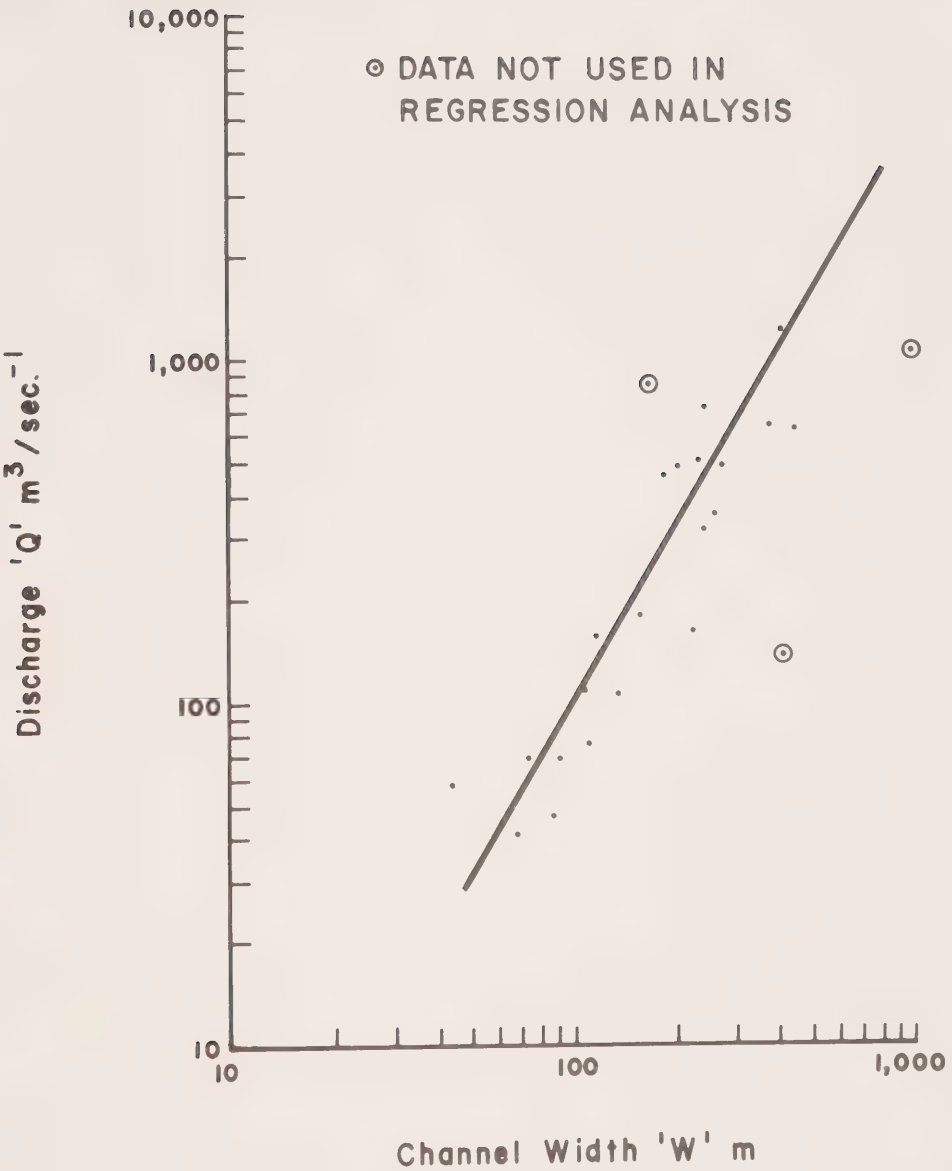


Figure 4. Plot of discharge versus channel width, Mackenzie Delta.

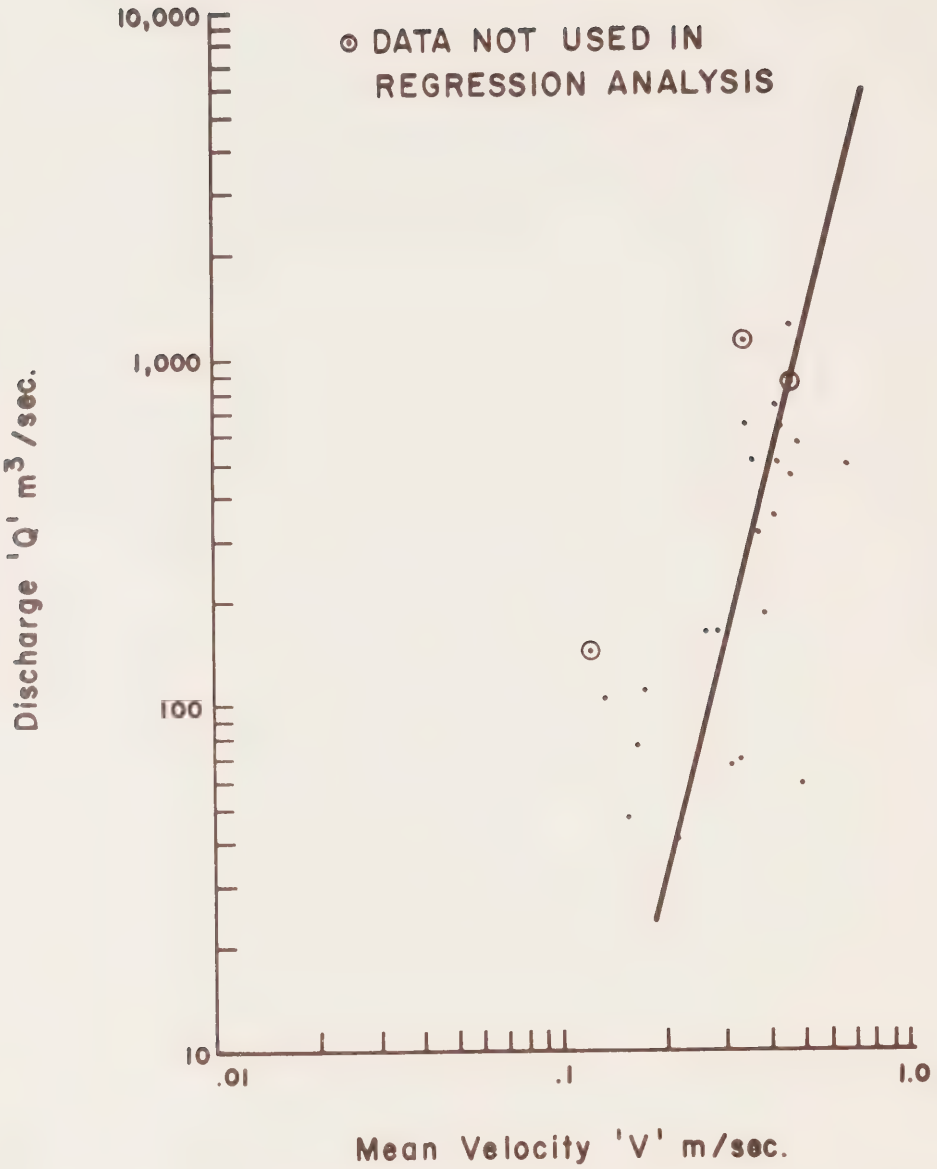


Figure 5. Plot of discharge versus mean velocity, Mackenzie Delta

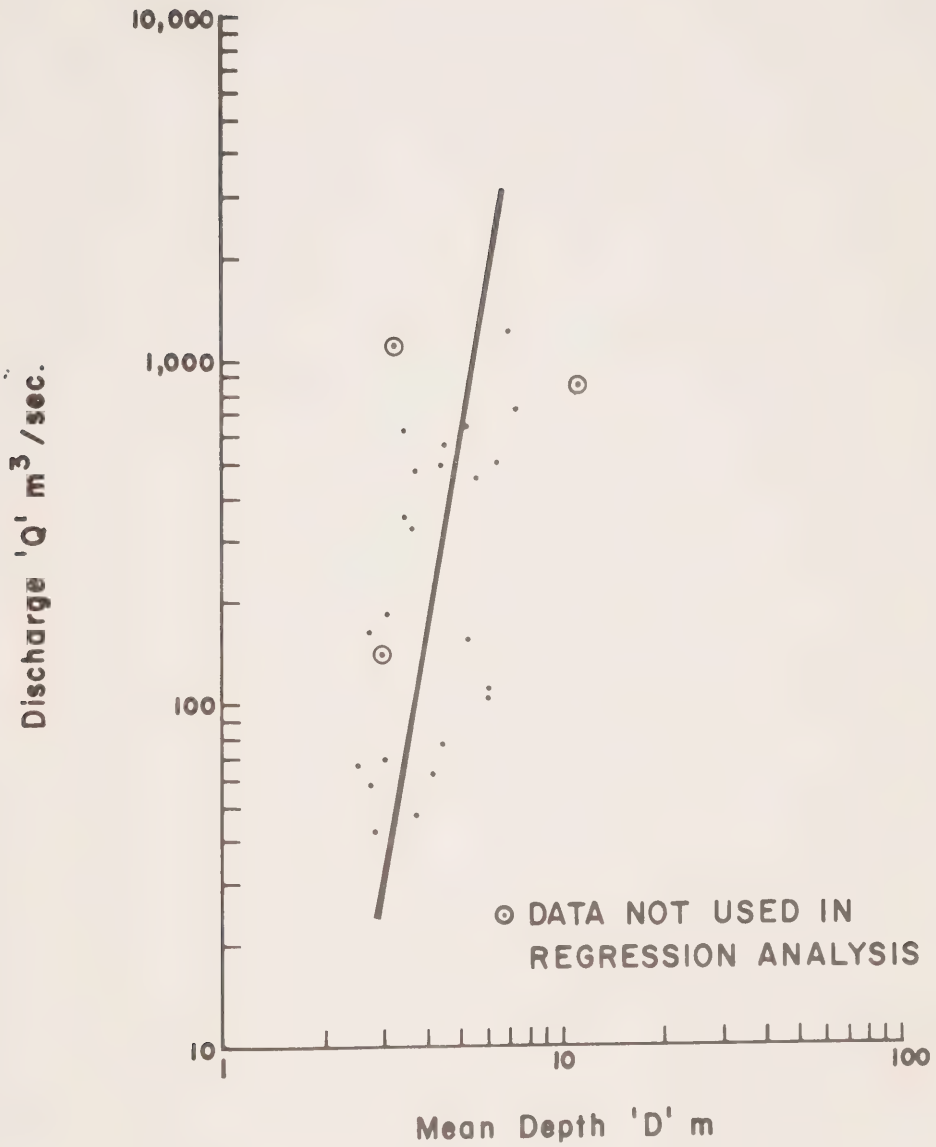


Figure 6. Plot of discharge versus mean depth, Mackenzie Delta.

TABLE 7

March 1972 Distribution of Flow in the Mackenzie Delta

	Discharge (m^3/sec)
Flow to Delta	= 2333.
Flow at A	= 0.
Flow in Middle Channel at v	= 2271.
Flow across Section V-V	= 2333.
Flow at w_1	= 15.7
Flow across Section W-W	= 1973.
Flow at x_1	= unknown
Flow across Section X-X	= 46.5
Flow at y_1	= 101.7
Flow across Section Y-Y	= 1926.4
Flow at z_1	= 436.2
Flow across Section Z-Z	= 1817.1

General ice conditions existing in the delta in March 1972, are noted as follows:

(1) Rough ice existed on many of the larger channels and on the main Mackenzie as illustrated on Figure 7.

(2) Channel ice heaving as well as shearing and sinking were observed on some of the smaller channels.

(3) Ice thicknesses tended to increase from south to north in the delta. Ice depth on wider channels tended to be thicker than on narrow channels.

Peak water level measured during break-up at Inuvik for a 9-year period was 7.13 m above winter ice level. Delta flooding was widespread in the spring of 1972 as can be noted in Figure 8. Discharge for this delta high water condition cannot be accurately determined as flow measurements of the Mackenzie at Point Separation are not available.

DISCUSSIONS

Summer Distribution of Flow

Data from several stations were omitted from the summer flow regression analysis because of apparent errors in measurement. These data are circled on Figures 3 to 6. Station A is a short but wide channel linking the Peel and Mackenzie Rivers at Indian Village. This channel is subject to reversals in flow (Henoch et al.) and velocities are low. It is believed that errors in depth were made by interpreting false reflection images as real on a depth sounder trace at Stations 11 and X. The regression analysis is based on data collected at 22 other sites in the delta between Point Separation and 68°35'N.

Linear correlation coefficients (Table 6) for width and area versus discharge are high. The correlation of mean depth with discharge is quite low as is indicated by the scatter of points shown in Figure 6. Similarly the mean velocity-discharge correlation coefficient is somewhat low. A total of the exponents yields the following:

$$b + f + m = .997$$

$$n + m = 1.000$$

Multiplication of the coefficients a, c and k yields:

$$a \times c \times k = 1.032$$

$$j \times k = 1.020$$

These are close to theoretical values.

The width-discharge correlation is noticeably high for the available data. This could reflect the 1971, July-August, measurement period when delta water levels were fairly low; at other stages another relationship may exist. A typical measurement site was usually steep-banked on one side and gently graded on the other.

The available 1971 data analysis does not consider possible changes in stage resulting from the backwater effects of storm surges in the coastal region. All equations are subject to revision as more data becomes available.

As summer discharge data are incomplete, the percentage of flow at each site cannot be computed at any given period. It should be noted that delta inflow can vary considerably during this period. For example, discharge records for the Mackenzie River at Norman Wells shows discharge varying from 19,000 to approximately 10,000 m^3/sec in the period from June 31 to August 28, 1971. Discharge through the sections listed in Table 1, therefore, cannot be calculated.



Figure 7. Mackenzie River at Point Separation. View from right bank, November 12, 1971.



Figure 8. Mackenzie Delta at 68°30'. View west from east shore, June 5, 1972.

Winter Distribution of Flow

Winter flow measurements in the delta are hindered by short days (approximately 6 hours of light/day during March), sub-zero temperatures, unpredictable weather, extreme ice thicknesses, rough ice conditions, freeze-up of equipment, etc. Sub-zero air temperatures which can cause equipment to freeze, affect the accuracy of discharge measurements; under these conditions, errors can exceed ±10% of the actual value. For example, more flow was measured leaving stations 13, 14 and 15 than was measured entering at Station 11.

The flow distribution network is greatly altered during the winter months (Table 4). Measured flow through Section Z-Z, 1,817 m^3/sec, represented 78 percent of the delta inflow from the Mackenzie and Arctic Red Rivers in March 1972. Of this amount, 41 percent travelled down the East Channel to Kugmallit Bay, and 59 percent moved to the west of Richards Island, 33 percent of which discharged into Shallow Bay via Reindeer Channel. Flow entering Shallow Bay from other sources = y_1 + 22 + Section X-X = 156 m^3/sec. This was 7 percent of delta inflow. Total accountable flow at the outlet was 1,972 m^3/sec and the total volume lost during measurement was 360 m^3/sec or 15 percent. It appears that very little of the Peel River flow entered Middle Channel. Data for other winter months are not available at present.

Ice Conditions

Shearing was observed on many of the smaller channels in November. As water levels dropped below the bottom of the ice surface, the weight of the combined ice and snow cover caused cracking and sinking often with the result that water was forced up onto the ice surface. This is a relatively common occurrence on delta channels (MacKay, 1965).

By the end of November, the build-up of ice in the shallower channels around the delta perimeter is responsible for a constriction of flow that can exert tremendous pressure on an ice cover. The pressure can cause heaving and overflow conditions in some areas of the delta.

In 1971, as the winter progressed and the ice thickened, flow became totally blocked in some shallow channels and flowing water was diverted into the deeper channels. During the measurement of discharge at Stations A, 10 and 25, water flowed onto the ice surface. This suggests that flow was either blocked downstream as at 10 and A, or restricted downstream as at 25. No heaving of the ice cover was evident and it is assumed that the ice thicknesses in the mid-winter of 1971 prevented such occurrences.

During the measurement of discharge in March, no slush or frazil ice was encountered under the ice cover anywhere in the delta. No polynas were reported and the slush ice which had formed earlier in the winter was already incorporated in the ice cover.

Rough ice covered sections of many large channels. These channels, being the last to freeze, were exposed to the movement of ice wreckage from upstream where the ice cover had broken up due to storms or surges in streamflow. The roughness of such ice surfaces is illustrated in Figure 7. Such conditions could be a factor in the trafficability of channels.

Break-up studies in the delta have been published by a number of authors (J.R. Mackay, 1960, 1961, 1963a, 1963b; D.K. MacKay, 1965, 1966). During break-up, ice jams form at sharp bends or at channel restrictions causing diversions, reversals of flow and overtopping of levees. The maximum height of flood marks diminishes northward in the delta as the break-up flood waters are distributed more effectively by many channels in the proximity of the ocean. One factor affecting the date of break-up and height of flooding is ice thickness which reaches a maximum by April. Water levels during the spring flood have been measured by the Inuvik Research Laboratory for the period 1964-1972. Daily levels, measured above winter ice level, were made at noon each day from early May until late June. For the period of record, a peak level of 7.13 m was recorded on June 7, 1972. Mean break-up for the period 1964-1971 at Inuvik is May 25.5. Break-up in 1972 occurred on June 4, approximately 10 days later than normal. Ice thicknesses in 1972 were greater than normal.

Ice thickness is a function of temperature, snow cover, channel depth, mixing and other factors. For example, winds tend to redistribute the snow cover causing bare areas and the development of sastrugi on channels. Mean annual snowfall in the delta varies as follows:

		MEAN ANNUAL	1972
Fort McPherson	(1941-70)	222.0 cm.	141.2 cm
Inuvik	(1957-70)	178.0 cm.	271.8 cm.
Aklavik	(1941-70)	99.1 cm.	-
Tuktoyaktuk	(1957-70)	55.6 cm.	74.4 cm.

From the mean annual snowfall data, there appears to be a latitudinal relationship, (see also Table 8) one that tends to hold for many climatic parameters in the transitional belt extending from the head of the delta to the Beaufort Sea. The 1972 snowfall (May excluded) was abnormal; for example, much of the snowfall in Inuvik (117.6 cm) occurred during October and was redistributed by the wind during the remainder of the winter.

In the southwest sector of the delta where levees are high, where vegetation is fairly tall and dense and where snowfall is relatively heavy, ice thicknesses are somewhat less than those measured farther north. Stations 6 and A (Figure 1) had mean ice depths of 0.8 m and 0.9 m respectively. In this vicinity, channels are smaller and snowfall is also greater. Above Fort McPherson, the Peel River ice was 1.0 m thick and to the west, ice on the Arctic Red River was 0.7 m. River entrenchment and tall dense vegetation helped to reduce the action of the prevailing winds in these areas. At stations near Aklavik, the ice thicknesses tended to be greater. The channel at station 13, which had the thinnest ice in the region, is narrow and is oriented normal to the prevailing winds. The ice was totally covered with hard-packed snow. At station C, the channel is wide (1,158 m) with long fetches subject to wind action which can affect the distribution of the snow cover. Much of the ice surface is rough with bare patches. Stations near Inuvik have less ice cover than the Aklavik ones due to an increased

TABLE 8

Ice thickness data, March 1972. Mackenzie Delta, N.W.T.

(Reference Figure 1)

Area	Station	Mean ice depth (m)
Fort McPherson and Arctic Red River	1	1.0
	6	0.8
	A	0.9
	2	0.7
Aklavik	9	1.4
	10	1.5
	11	1.5
	12	1.2
	13	1.1
Inuvik	16	1.2
	17	1.0
	18	1.3
	19	1.1
Reindeer Depot to Tununuk	20	1.2
	21	1.4
	22	1.3
	23	1.5
	24	1.6
	25	1.5

snowfall. Station 18, with the greatest ice thickness in this area, is located on the wide Middle Channel (1,113 m); its orientation is parallel to the prevailing wind direction. At Inuvik, station 16 has greater ice thicknesses due to its width, less snow cover and a plowed winter road. The stations north of Inuvik which receive lesser amounts of snow and, additionally have lower mean monthly temperatures, lower levee heights and less vegetative cover, also have the greater ice thicknesses.

CONCLUSIONS

The distribution of flow in the Mackenzie Delta is greatly altered by the formation and development of an ice cover. Flow in channels having shallow sections or shallow mouths is diverted into deeper channels. During the month of March 1972, approximately 78 percent of the flow through the delta remained in the Middle Channel as far north as Langley Island near Tununuk Point. Flow from the Peel River remained on the west side of the delta, judging by discharge measurements made in the Aklavik region. Ice thicknesses tended to increase latitudinally in the delta. Despite the unusual snowfall pattern, greater than normal ice thicknesses, as well as a later break-up date combined with record water levels were observed in 1972.

Cross-sectional area, width, mean depth, and mean velocity of a channel can be represented as a function of the discharge in the form of a simple power equation. The mean values for delta channels during mid-summer 1971, can be represented by:

$$A = 13.6\ Q^{.731}$$

$$W = 8.47\ Q^{.554}$$

$$V = 0.075\ Q^{.269}$$

$$D = 1.63\ Q^{.174}$$

At each station the power function representing these relations is similar but involves local variations. There is insufficient data at present to derive these local equations. Cross-sectional area is the best predictor because it involves two channel parameters.

From a hydrological point of view, the Mackenzie Dalta is the most complicated region in northern mainland Canada that is affected by oil and gas exploration. As such, it should be studied and monitored intensively in order to determine the effects of hydrocarbon development and to minimize its impact on the ecosystems and on the critical environment of the delta.

RECOMMENDATIONS

Available streamflow data for the Mackenzie Delta is insufficient to develop a set of stage-discharge curves for the major delta channels. More discharge measurements should be made and in order to develop a reasonable knowledge of delta flow, a network of water level recorders should be installed. The Water Survey of Canada is expected to carry out the operation in 1973.

Past flooding in the delta should be studied in detail in order to determine the maximum height of flood stage, the regions in the delta most susceptible to flooding and the causes of flooding in these regions. Glaciology Division hopes to broaden studies into these aspects in 1973.

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APPENDIX I

Measurement site descriptions

1. Station Locations, 1-25
2. Station Locations, A - C
3. Miscellaneous discharge measurement locations, I-XII

MACKENZIE DELTA, N.W.T.

Station Locations

1 - Peel River above Fort McPherson - gauging station

2 - Arctic Red River at Martin House - gauging station

3 - Mackenzie River above Arctic Red River - gauging station

4 - Husky Channel

5 - Phillips Channel

6 - Peel Channel

7 - Kalinek Channel

8 - East Channel - Mackenzie River

9 - Peel Channel above Aklavik

10 - Pokiak Channel above Aklavik

11 - West Channel (Mackenzie R.) below Aklavik Channel

12 - Aklavik Channel above Schooner Channel

13 - Nikoluk Channel

14 - Leland Channel

15 - Hvatum Channel

16 - East Channel (Mackenzie R.) at Inuvik

17 - Kalinek Channel - N.W. of Inuvik

18 - Middle Channel (Mackenzie R.) above Napoiak Channel

19 - Napoiak Channel

20 - Middle Channel (Mackenzie R.) west of Williams Island

21 - East Channel (Mackenzie R.) below Williams Island

22 - Marcus Channel

23 - Reindeer Channel

24 - East Channel (Mackenzie R.) below Tununuk Point

25 - Channel to west of, and below Tununuk Point

MACKENZIE DELTA, N.W.T.

Station Locations

A - Channel below Indian Village

B - East Channel above Kalinek Channel

C - Middle Channel above Horseshoe Bend

MACKENZIE DELTA, N.W.T.

Miscellaneous Discharge Measurements, Summer 1971

LOCATION	
I	Small channel between Husky and Peel Channels.
II	Husky Channel above Phillips Channel.
III	Peel Channel above junction with Husky Channel.
IV	Husky Channel above junction with Peel Channel.
V	Aklavik Channel between Schooner and Taylor Channels.
VI	Taylor Channel near Aklavik Channel.
VII	West Channel below Hvatum Channel.
VIII	Schooner Channel above Napoiak Channel
IX	Napoiak Channel below Schooner Channel.
X	Oniak Channel at Middle Channel.
XI	Channel below Oniak Channel to southwest of Harrison Island.
XII	Oniak Channel at south end of Harrison Island.

APPENDIX II

Streamflow data, Mackenzie Delta

Table 2. Summer 1971
Table 3. Summer 1971
Table 4. March 1972
Table 5. April - October 1972.

Table 2. Streamflow data, Mackenzie Delta, during summer 1971.

Location	Area "A" m^2	Width "W" m	Mean Depth "D" m	Discharge "Q" m^3 sec^{-1}	Mean Velocity "V" m sec^{-1}	Stage m	Surface Temperature °C	Date Day/mo./yr.
4	214.	73.	3	68.7	.32		17°	27/7/71
5	315.	85.	3.7	46.8	.15		17°	27/7/71
6	1,042.	185.	5.6	456.9	.45		9°	8/8/71
10	187.	68.	2.8	41.1	.22		18°	9/7/71
11	3,341.	992.	3.4	1,091.3	.33		16°	8/7/71
13	655.	109.	6.0	109.9	.17	26.53	17°	8/7/71
14	474.	156.	3.0	179.1	.38	26.53	16°	7/7/71
15	883.	243.	3.6	314.8	.36	26.75	15°	7/7/71
16	620.	227.	2.7	102.3	.27	26.46	17°	23/7/71
19	1,240.	273.	4.4	498.7	.41		16°	1/7/71
A	1,198.	417	2.9	139.2	.12	22.19	16°	28/8/71

Table 3. Streamflow data, miscellaneous sites, Mackenzie Delta, summer 1971.

Location	Area "A" m^2	Width "W" m	MeanDepth "D" m	Discharge "Q" m^3 sec^{-1}	Mean Velocity "V" m sec^{-1}	Stage m	Surface Temperature °C	Date Day/mo./yr.
I	119.	44.	2.7	57.8	.49		10°	18/08/71
II	811.	135.	6.0	104.2	.13		17°	27/07/71
III	1,434.	232.	6.2	503.5	.35		16°	9/07/71
IV	487.	111.	4.4	75.4	.16		18°	9/07/71
V	1,218.	271.	4.5	576.3	.47		18°	10/07/71
VI	220.	89.6	2.5	66.5	.30		17°	10/07/71
VII	1,486.	441.	3.4	623.2	.42		14°	7/07/71
VIII	592.	117.	5.1	153.8	.26		14°	1/07/71
IX	1,925.	374.	5.2	645.5	.34		14°	1/07/71
X	1,846.	167.	11.1	841.5	.46		15°	30/06/71
XI	2,781.	402.	6.9	1,233.6	.45		14°	30/06/71
XII	877.	261.	3.4	349.1	.40		14°	30/06/71

Table 4. Streamflow data, Mackenzie Delta, March 1972.

Location	Area "A" m^2	Width "W" m	Mean Depth "D" m	Discharge "Q" m^3 sec^{-1}	Mean Velocity "V" m sec^{-1}	Stage m	Mean Ice Depth	Date Day/mo./yr.
1	507	262	1.9	62.2	.12		1.0	10/3/72
2	159	137	1.2	8.4	.05		.70	2/3/72
3	7,598	655	11.6	2,262.4	.30		1.1	21/3/72
4	NO WINTER DATA AVAILABLE DUE TO WEATHER AND LANDING CONDITIONS							
5	" "	"	"	" "	"	"	"	
6	405	149	2.7	38.4	.10	20.17	.79	23/3/72
7				0	0			
8				0	0			
9	1,442	256	5.6	8.7	.01		1.4	14/3/72
10	19	27	1.4	OVERFLOW	0		1.5	14/3/72
11	986	762	1.3	30.8	.03	24.71	1.5	15/3/72
12	857	215	4.0	37.8	.04		1.2	15/3/72
13	462	95	4.9	0	0	25.35	1.1	15/3/72
14	196	130	1.5	5.8	.03	25.89	1.4	14/3/72

Table 4 (cont.) Streamflow data, Mackenzie Delta, March 1972.

Location	Area "A" m^2	Width "W" m	Mean Depth "D" m	Discharge "Q" $m^3 sec^{-1}$	Mean Velocity "V" $m sec^{-1}$	Stage m	Mean Ice Depth	Date Day/mo./yr.
15	587	216	2.7	27.4	.05	26.48	1.1	14/3/72
16	328	137	2.4	0	0	25.65	1.2	16/3/72
17	753	328	2.3	0	0		1.0	22/3/72
18	14,800	1,113	15.2	1,926.4	.13		1.3	22/3/72
19	539	189	2.9	0	0		1.1	22/3/72
20	15,624	610	25.6	1,814.4	.12		1.2	20/3/72
21	958	468	2.0	10.3	.01		1.4	20/3/72
22	234	151	2.8	7.6	.03		1.3	20/3/72
23	8,658	506	17.1	605.0	.07		1.5	17/3/72
24	4,269	840	5.1	748.3	.18		1.6	17/3/72
25	459	140	3.3	OVERFLOW 27.6	.06		1.5	17/3/72
A	348	268	1.3	OVERFLOW 0	0	20.97	snow .9	23/3/72
B	1,135	244	4.7	0	0		1.0	30/3/72
C	12,183	1,158	10.5	1,901.2	.16		1.4	6/4/72

Table 5. Streamflow data, Mackenzie Delta, April-October 1972.

Location	Area "A" m^2	Width "W" m	Mean Depth "D" m	Discharge "Q" $m^3 sec^{-1}$	Mean Velocity "V" $m\ sec^{-1}$	Stage m	Surface Temperature °C	Date Day/mo./yr.
1						7.84	16	17/06/72
1						4.73	19	17/07/72
1	1,125	283	4.0	490.4	.44	4.68	18	18/07/72
1						5.44		29/08/72
1	1,376	305	4.5	1,016.4	.74	5.60	7	08/09/72
2	145	134	1.1	9.7	.07	1.52	.6	12/04/72
2						2.28	.6	18/05/72
2	713	233	3.1	613.0	.86	3.73	15	16/08/72
2	479	192	2.5	285.6	.60	2.70	16	22/07/72
2	428	181	2.4	223.4	.52	2.49	12	29/08/72
2	472	191	2.5	233.8	.50	2.64	2	21/09/72
3						10.32	17	12/07/72
3	13,206	1,149	11.5	17,052.0	1.29	10.11	17	13/07/72
3						9.78		15/08/72
3						8.61	8	09/09/72
16	744	201	3.7	481.6	.65	26.64		10/08/72
16						25.55		14/09/72

Table 5 (cont.) Streamflow data, Mackenzie Delta, April-October 1972.

Location	Area "A" m^2	Width "W" m	Mean Depth "D" m	Discharge "Q" $m^3 sec^{-1}$	Mean Velocity "V" m sec^{-1}	Stage m	Surface Temperature °C	Date Day/mo./yr.
						25.52		15/09/72
16						25.70		18/09/72
16						25.89		20/09/72
16						25.64		25/09/72
16						26.23		27/09/72
16						25.52	running ice	02/10/72
16						25.70	.6	04/10/72
B	1,739	241	7.2	719.6	.41	23.65		14/08/72

Report

on the

STABILITY OF RIVER BANKS AND SLOPES ALONG THE LIARD RIVER AND MACKENZIE RIVER, NORTHWEST TERRITORIES

by

J. Chyurlia

Technical Report 4 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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REPORT ON THE STABILITY OF RIVER BANKS AND SLOPES ALONG THE LIARD RIVER AND MACKENZIE RIVER NORTHWEST TERRITORIES

by

J. Chyurlia

Introduction

The Glaciology Division of the Water Resources Branch, Inland Waters Directorate, Department of the Environment, carries out studies of various problems associated with the proposed construction of a pipeline along the Mackenzie River. The scope of this report is the investigation of the stability of river banks in the Mackenzie River Basin.

Two study areas were chosen: (1) the area around Fort Simpson which includes the lower reaches of the Liard River (Fig. 1); (2) a stretch of the Mackenzie River from Little Chicago to the settlement of Arctic Red River (Fig. 2).

Fort Simpson/Liard River Area

Two types of mass movements were observed in this area. The most widespread type is the collapse and surficial sloughing of river banks. The failures appeared to be planar i.e. the failure plane was rectilinear and parallel or quasi-parallel to the slope surface. This phenomenon leads either to the retreat or to the decline of river banks. The second, less widespread type, is a combination of *rotational* and *translational* failures, (Skempton and Hutchinson, 1969), which involve the movement of a considerable fraction of the slope material rather than merely the near-surface materials. Translational elements are present to a degree reflecting the local stratigraphy. Possibly, an increase in pore-water pressure along potential failure surfaces is responsible for the initial collapse of these slopes. Some failure surfaces may coincide with geological contacts. The presence of permafrost was noted in these slides and it is possible that melting permafrost contributes substantially to the quantity of pore-water present.

The sloughing of river banks is intimately related to the flood frequencies and stage-discharge relationships of the rivers concerned. The rectilinear nature of the failure planes suggests two things: (1) the material that fails behaves solely frictionally at the time of failure; (2) in the case of slopes comprised predominantly of bedrock, the failure planes may be predetermined by the contact between the bedrock and the overlying residual soil mantle. The mantle slides down-slope exposing bedrock to renewed weathering and possible failure at a later date.

Whichever case may occur, the mode of failure is related to the resistance which the materials can provide to resist the shearing stresses. In the long-term sense, the residual angle of shearing resistance (ϕ_r) is known to be an important parameter governing the material's susceptibility

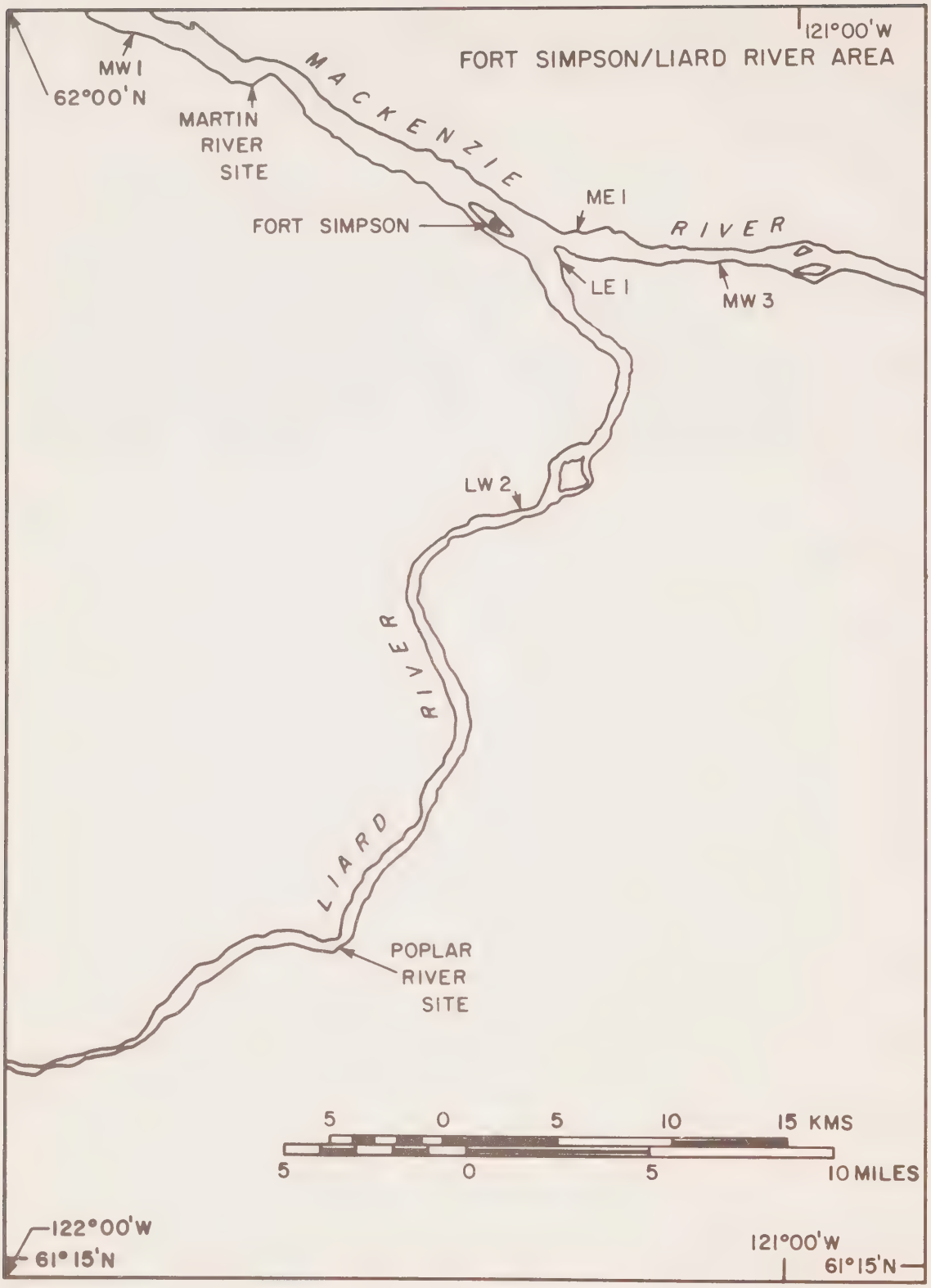


Figure 1. Slopes and slides surveyed on the Liard and upper Mackenzie Rivers.

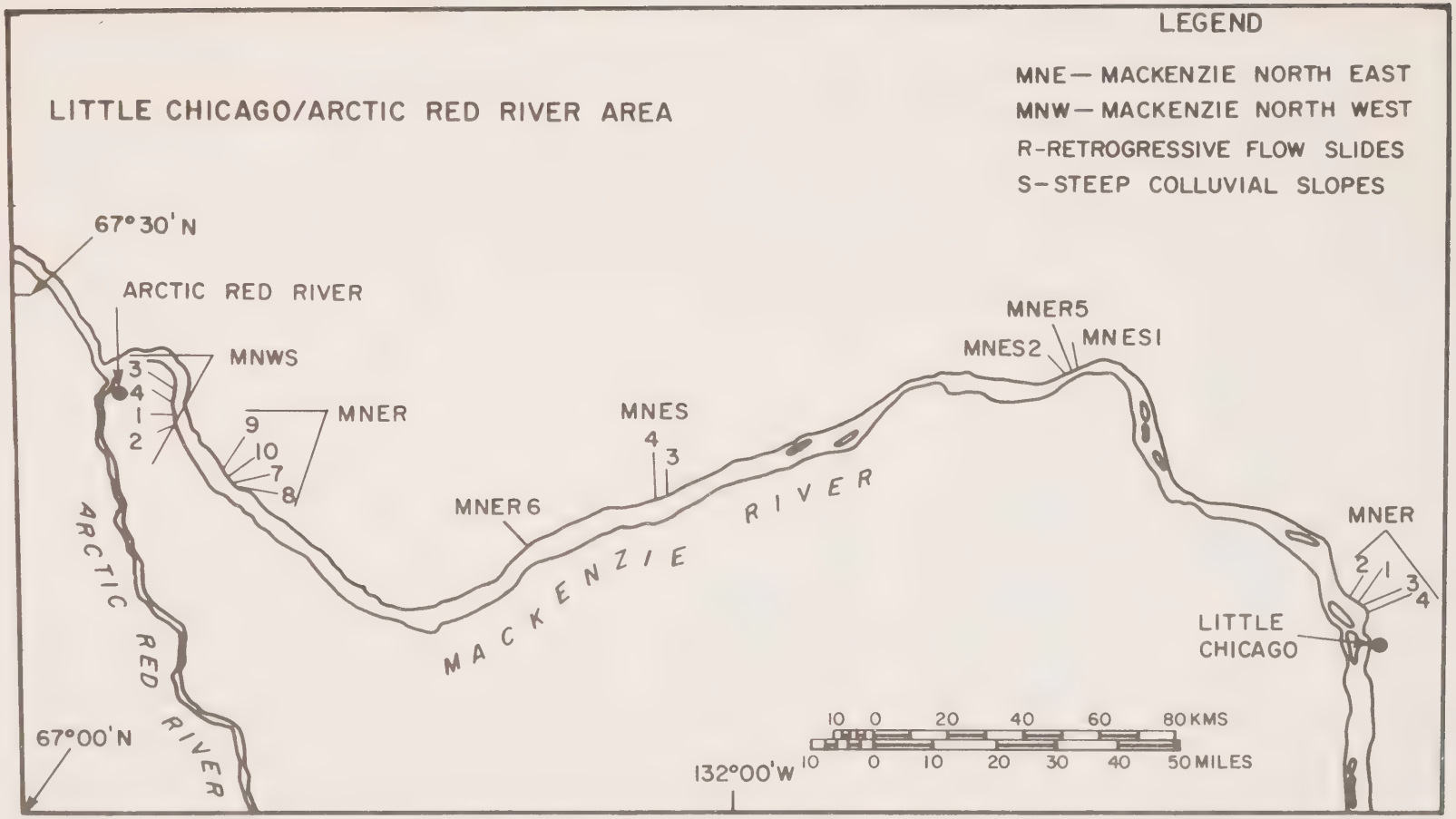


Figure 2. Slopes and slides surveyed on the lower Mackenzie River.

to fail along discrete and geometrically specifiable surfaces (Skempton, 1964). Skempton and DeLory (1957), Hutchinson (1967), and Carson (1969) have shown that in the case of near-surface movements the computation of the stability of a slope may be made with the assumption that the plane of failure is parallel to the slope surface without an appreciable loss of accuracy in the results; this is known as the "infinite slope model".

The infinite slope model has been used to demonstrate that the slope angle i assumes a value intermediate between the angle of shearing resistance $\emptyset_r$ and an angle θ computed as follows:

$$\theta = \frac{(\gamma - \gamma\omega)}{\gamma\omega} \arctan (\emptyset_r)$$

where: γ is the saturated unit weight of the soil, $\gamma\omega$ is the unit weight of water in g/cm^{-3}

since: $[(\gamma - \gamma\omega)/\gamma\omega] \chi \sim \frac{1}{2}$

$$\theta = \tfrac{1}{2} \arctan \emptyset_r$$

The relationship between the slope angle and the action of river erosion at the base of the slope is of particular interest. Strahler (1950) suggested that river banks adjust themselves to the agressive basal action of streams by maintaining their steepest possible slopes. This view has been supported in recent years by the works of Carson and Petley (1969) and Chyurlia (1970). In the case of freely-degrading slopes, i.e. slopes with no undercutting, successive mass-movements will eventually cause the slope angle to decline to an ultimate value given by θ. On the other hand, the aggressive action of rivers (either by downcutting or by lateral erosion) intermittently oversteepens the slopes which may be stable at angles as high as "$\emptyset$" depending on seepage conditions. Thus, a dynamic equilibrium is achieved between the river banks and the river. The parameters defining this state of equilibrium relate to many environmental considerations amongst which topography, climate and vegetation play a role.

Seven river banks were surveyed and sampled in this area. Unfortunately, the sampling was not sufficiently detailed to reveal any interesting correlations between $\emptyset_r$ (as measured by a direct shear apparatus) and the slope angles. Slope angles ranged between 35° and 47° and $\emptyset_r$ ranged between 27° and 52°. This variation is considerably greater than that of the river banks at the second study area south of Inuvik, N.W.T.

The variation may be due to the effects of other variables and processes. Measurements of ice-shove heights and driftwood heights revealed that in some places the Liard River may rise as much as 10m (33 ft) during spring flooding. Thus, the removal of bank materials by scouring may be a more significant process of erosion that the "undercutting-mass movements" mechanism postulated earlier. It was also noticed that active bank erosion was spatially associated with a lack of vegetation. Vegetation-covered slopes appeared quite stable even in cases where the inclination approached 50 degrees.

The implication is that the removal of vegetation either by natural processes (e.g. fire, flooding, ice rafting) or by human interference (e.g. construction) will promote a high degree of bank erosion. It seems very possible that the removal of vegetation by ice shoving during spring flooding is the principal agent of vegetation removal which initiates high rates of bank erosion by both collapse and scouring.

Two translational/rotational slides were seen in this area. One was on the Mackenzie River at the mouth of the Martin River (61° 57'N, 121° 40'W). The other was on the Liard River near the mouth of the Poplar River (61° 26'N, 121° 22'W) (Fig. 1). At both sites the evidence suggests that several episodes of failure have occurred.

At both sites the failure occurred near the top of the slope A bottleneck is present at both sites as tongues of debris extend into the river. The debris tongue is better developed at the Poplar River site than at the Martin River site. Both tongues are being eroded by the river at their bases. Tree ring evidence indicates that the Martin River slide occurred in 1967, and that the Poplar River slide occurred in 1969. Thus, the debris tongue of the Martin River slide has been eroded for a longer time than the tongue of the Poplar River slide.

Tree-ring evidence also suggests that minor failures have occurred intermittently at these sites for numerous years. This may be an indication of *either* progressive failure of the materials *or* the intermittent triggering of slides; the latter were caused by *either* the undercutting of the slopes by the river *or* the attainment of critical pore-water pressures at randomly spaced intervals. Tension cracks suggest that further movements are possible. At the Poplar River site, tension cracks extend to a depth of 6.1 m(20 ft) behind the scarp.

Two hypotheses may explain these slides (1) progressive-failure of the materials occurred; eventually the slope becomes too steep to support the soil causing a slide. In the case of cohesive materials, the height of the slope is a factor. Undercutting of the slope may promote instability by oversteepening the slope; (2) melting permafrost causes increases in pore-water pressures at geological contacts. Such increases in pore-water pressure act to diminish the shear strength of the soil along the contact zone. If the material is cohesive (such as a clayey soil), then failure will occur by spreading; if the material is granular, then failure will occur by spontaneous liquifaction (Terzaghi and Peck 1967, pp. 434-438).

At both sites the presence of water in slide debris and melting permafrost was observed. Also, in both cases there is a geological contact. At the Martin River site, sands and silts overlie a stiff clayey soil. At the Poplar River site, the base of the slope is composed of flat-lying limestones and calcareous shales. These more resistant materials at the base of the slope introduce a translational element in the slide geometry. The two hypotheses just presented are not mutually exclusive.

An *a priori* analysis of the stability of such slopes is rendered quite difficult because of the number of variables involved not only with respect to the materials which comprise the slopes but also with hydrological,

topographical and climatic considerations. This, however, does not mean that it is impossible to detect areas susceptible to this kind of failure. It is amenable to engineering design purposes.

Inspection of tree-rings at possible construction sites is likely to reveal progressive failure of earth materials in areas where slow movements have been occurring intermittently. The presence of tension cracks on slopes indicates incipient instability of slopes particularly if the slopes are being undercut by stream erosion. Seepage of pore-water through layers overlying bedrock or impermeable formations indicates the possibility of a critical build-up in pore-water pressures in confined soil layers which may promote sliding.

Little Chicago/Arctic Red River Area

Eighteen slopes were investigated along the Mackenzie River from Little Chicago to the settlement of Arctic Red River (Fig. 2). Ten of the slopes were retrogressive flow slides and eight were steep colluvial slopes making up the river bank. The retrogressive flow slides were confined to glaciolacustrine deposits and they are better developed on the right bank of the river than on the left bank.

The ten flow slides (Fig. 3 to 7, labelled MNER1 to MNER10) were all associated with melting permafrost. In eight of these ten slides, the melting permafrost was caused by fires in the overlying vegetation cover. The slides have an amphitheatre-shaped source area, a bottleneck and one or more debris tongues. The debris flows like a viscous slurry and may form discrete channels, rectangular in shape, up to four feet wide and three feet deep.

It is evident that these slides renew their activity every year because of melting permafrost during the summer. Therefore, their magnitude is in part dependent on their age. The largest slide investigated (MNER5) is 98.4 m (323 ft) high. Tree-ring evidence shows that movement has been occurring on the side of the bottleneck for at least fifty years; thus, the slide is somewhat older than this. A possible correlation may exist between episodes of movement and climatic variables, e.g., precipitation and temperature, since the amount of material removed every season is proportional to the amount of permafrost melted. However, an insufficient number of tree-core samples were taken to substantiate this hypothesis.

Samples of the flowing material were collected. The field moisture content was assessed as well as the saturated and dry unit weights of the material . The long profiles of the slides were surveyed by means of an altimeter, a range pole and a Brunton Compass.

In the laboratory, the liquid limit, the plastic limit, the grain-size distribution and the residual-strength parameters of the materials were measured. The residual shear strength was determined by means of a direct shear apparatus. The samples were remoulded and the slurry was allowed to consolidate under the test load prior to the application of strain. The tests were carried out with the water-saturated soil and the samples were allowed to drain during the test. Thus, the strength parameters (c, the cohesion, and

ϕ_r) are in terms of effective stresses.

The field and laboratory data for each of the slopes surveyed are summarized in Table I. No apparent correlations exist between the measured variables. The dimensionless stability number, Ns, was computed for each slope according to the relationship:

$Ns = \gamma.H/c$ where c is the cohesion lb/ft^2, H is the height of the slope (ft), and γ is the unit weight of the soil (lb/ft^3),

(Scott, 1963, op. cit. Carson, 1971, p. 110). There is a very weak negative correlation between the stability number and the plasticity of the material. (The plasticity is the numerical difference between the liquid limit and the plastic limit of a soil).

The weakness of the correlations between the strength parameters, the material properties and the slope geometry indicates that these flow slides are probably *not* related to the frictional strength but to the liquid limit of the materials. If the ice content of the permafrost prior to melting exceeds or is close to the liquid limit of the material derived from the melting permafrost, then a flow slide will occur. The amount of material moving in a given season is thus related to the amount of permafrost melted. Removal of debris by river erosion at the tongue may cause further movement of these flow slides.

The eight steep river banks are composed of materials which vary considerably according to their textural properties (Fig. 8 - 17). In several cases, the materials are derived *in situ* from disintegrating bedrock.

The samples were analyzed in direct shear apparatus in order to determine their angle of shearing resistance. The tests were performed with dry specimens rather than wet specimens; thus the angles are in terms of total normal stress. Because these samples are coarser than those from the flow slides (Fig. 8-17, distribution diagrams), it is unlikely that they attain full saturation in the field. The slope angles (Fig. 18-21) were compared to the ϕ angles determined in the laboratory. In all cases the slope angle (i) had a value intermediate between ϕ and θ as derived in section 2.

This relationship indicates that the infinite slope model mentioned earlier may provide a satisfactory explanation for the stability of these steep banks. The ultimate angle of stability of these banks would be θ assuming that in the long-term case complete saturation of the material occurs. Therefore, all slopes at angles greater than θ cannot be considered stable in the long-term sense. It is evident that the aggressive action of the river at the base of the slopes oversteepens them and maintains them at angles greater than θ but less than ϕ_r

Conclusions

From the limited evidence considered, two conclusions may be drawn with regard to the stability of river banks in this area. In the case of steep colluvial slopes, the infinite slope model (Skempton and DeLory, 1957) may prove to be adequate in the prediction of the stability. In the case of mudflows and retrogressive slides, it may be concluded that the critical

TABLE I

Material properties of flow slide slopes MNE 1 to MNE 10

Site	Slope Angle (deg)	Friction Angle (deg)	Cohesion g/cm^2(psf)	Height M (ft)	Dry Wt. g/cm^3(pcf)	Saturt. Wt. g/cm^3(pcf)	Liq. Limit	Pla. Limit	Mean Grain Size (mm)	Unif. Coeff.
MNE 1	12	1½	156.24 (320)	32.92 (108)	1.35 (84.2)	1.85 (115.3)	52.8	26.3	0.0020	30.0
MNE 2	17	13½	41.01 (84)	32.00 (105)	1.32 (82.6)	1.83 (114.4)	39.0	22.0	0.0040	26.0
MNE 3	20	24½	14.16 (29)	28.96 (95)	1.65 (102.8)	2.04 (127.1)	34.7	22.0	0.0048	2.0
MNE 4	18½	9½	3.42 (7)	28.96 (95)	1.48 (92.7)	1.94 (120.8)	50.5	25.3	0.0062	6.7
MNE 5	15	23	76.17 (156)	98.45 (323)	1.58 (98.6)	1.99 (124.5)	33.1	19.4	0.0021	17.5
MNE 6	13	11½	63.47 (130)	33.22 (109)	1.43 (89.3)	1.90 (118.6)	45.0	21.5	0.0012	17.5
MNE 7	12½	29½	24.41 (50)	36.58 (120)	1.56 (97.3)	1.98 (123.7)	33.3	22.7	0.0080	45.5
MNE 8	20½	17	53.22 (109)	32.92 (108)	1.24 (77.5)	1.78 (111.2)	72.9	31.4	0.0007	15.4
MNE 9	18	33½	37.11 (76)	36.27 (119)	1.63 (101.9)	2.03 (126.9)	----	----	0.0550	62.0
MNE 10	16	33	----------	36.27 (119)	1.62 (101.1)	2.02 (126.1)	27.0	19.2	0.0300	666.7

variable is the ice content of the permafrost in the glacio-lacustrine deposits. Thus, if an attempt is made to predict such flows, the thermal properties of the permafrost as well as the materials overlying the permafrost should be considered both in the spatial sense and in the "disturbance - response" sense. Detailed work on tree-ring data would probably reveal interesting relationships both within one mudflow and between several mudflows.

Acknowledgements

The assistance of the following people is gratefully acknowledged; Messrs. W. Henoch, M. Parker, J. Riddle, R. Anderson, D. Outhet, and the technicians at the Materials Testing Laboratory of the Department of Public Works, Ottawa.

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APPENDIX 1.

Figures 3-7. Flow slide profiles MNE1 to MNE10.

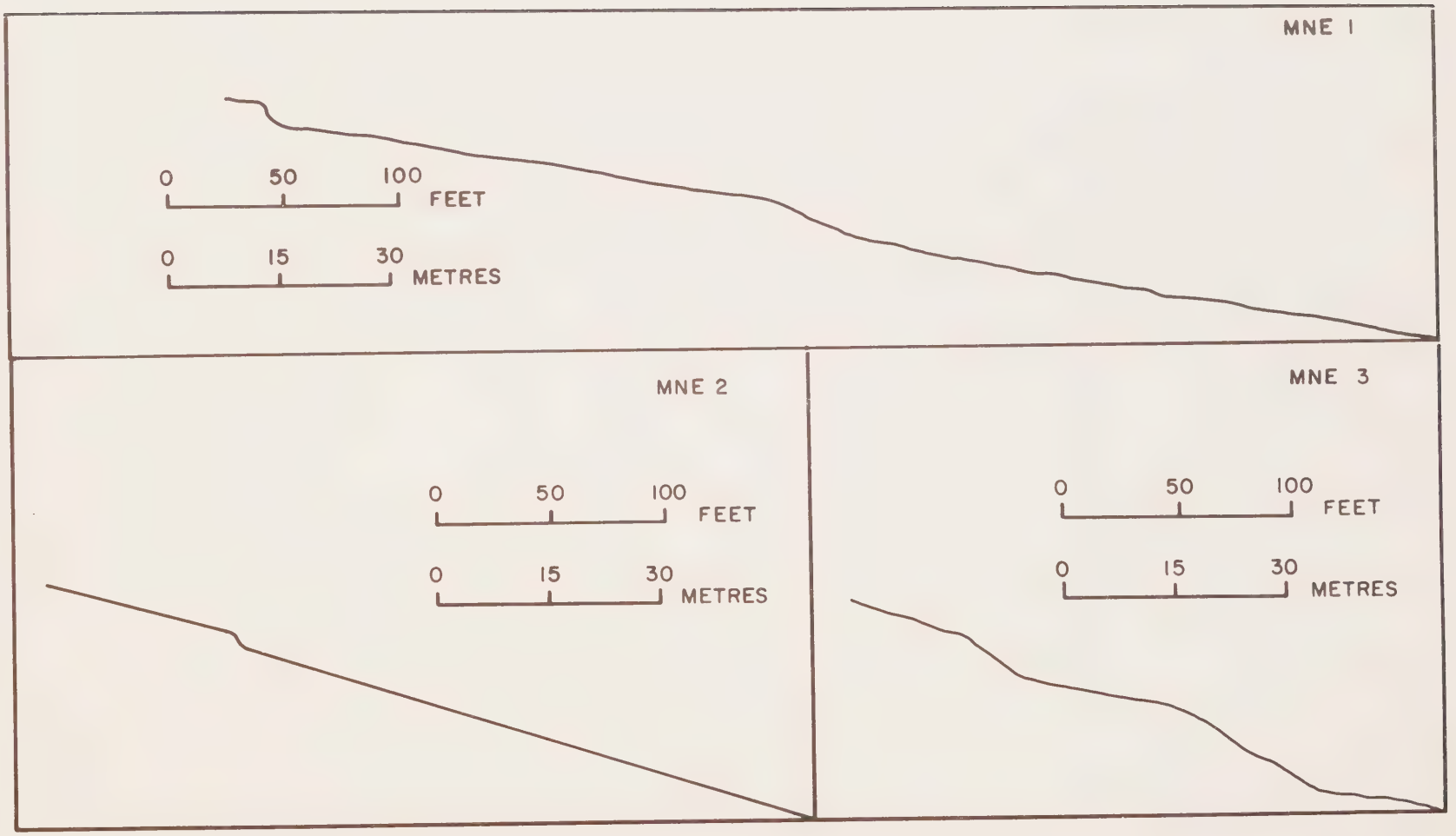


Figure 2. Profiles of retrogressive flow slides near Little Chicago.

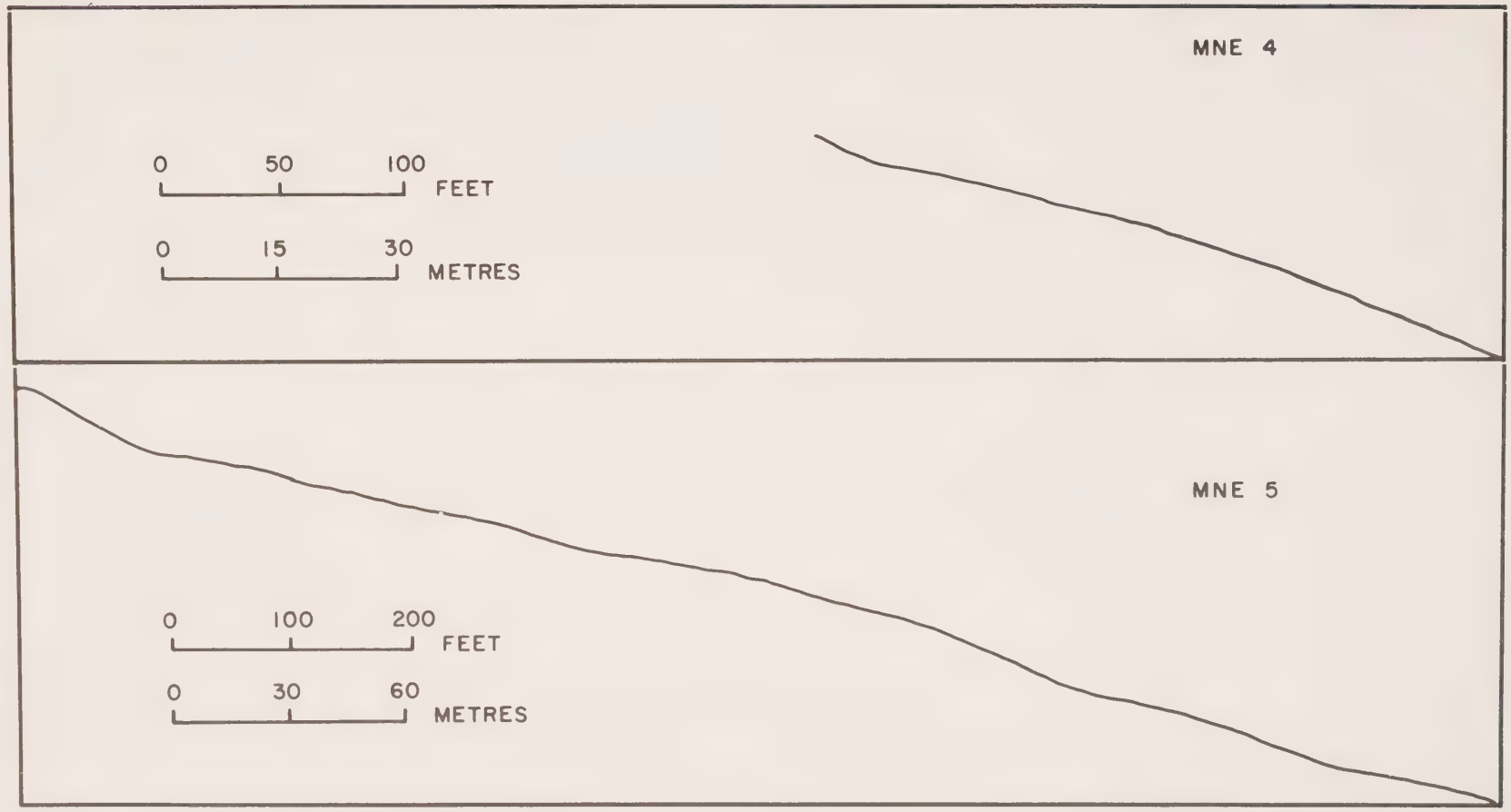


Figure 4. Profiles of retrogressive flow slides.

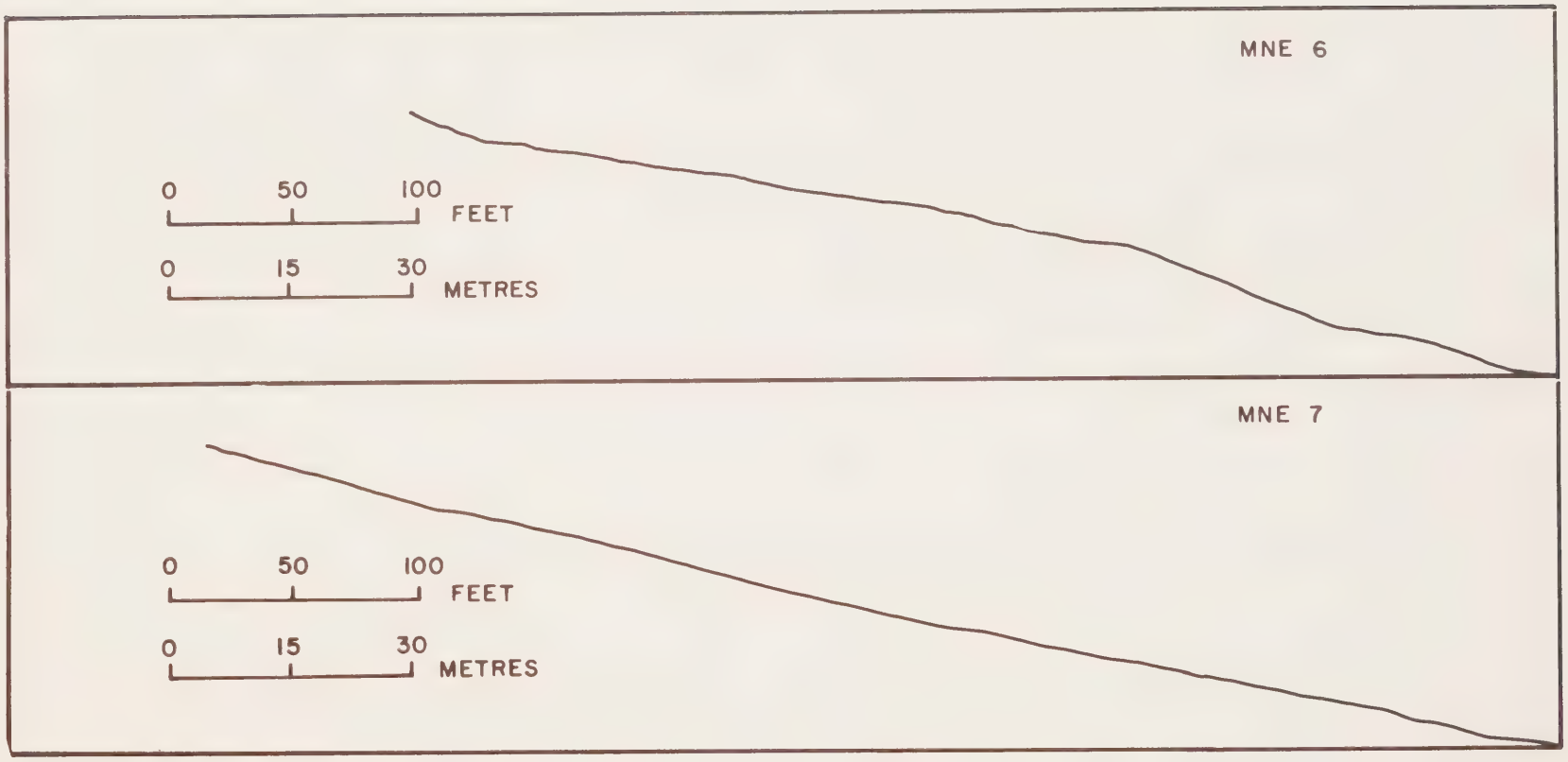


Figure 5. Profiles of retrogressive flow slides.

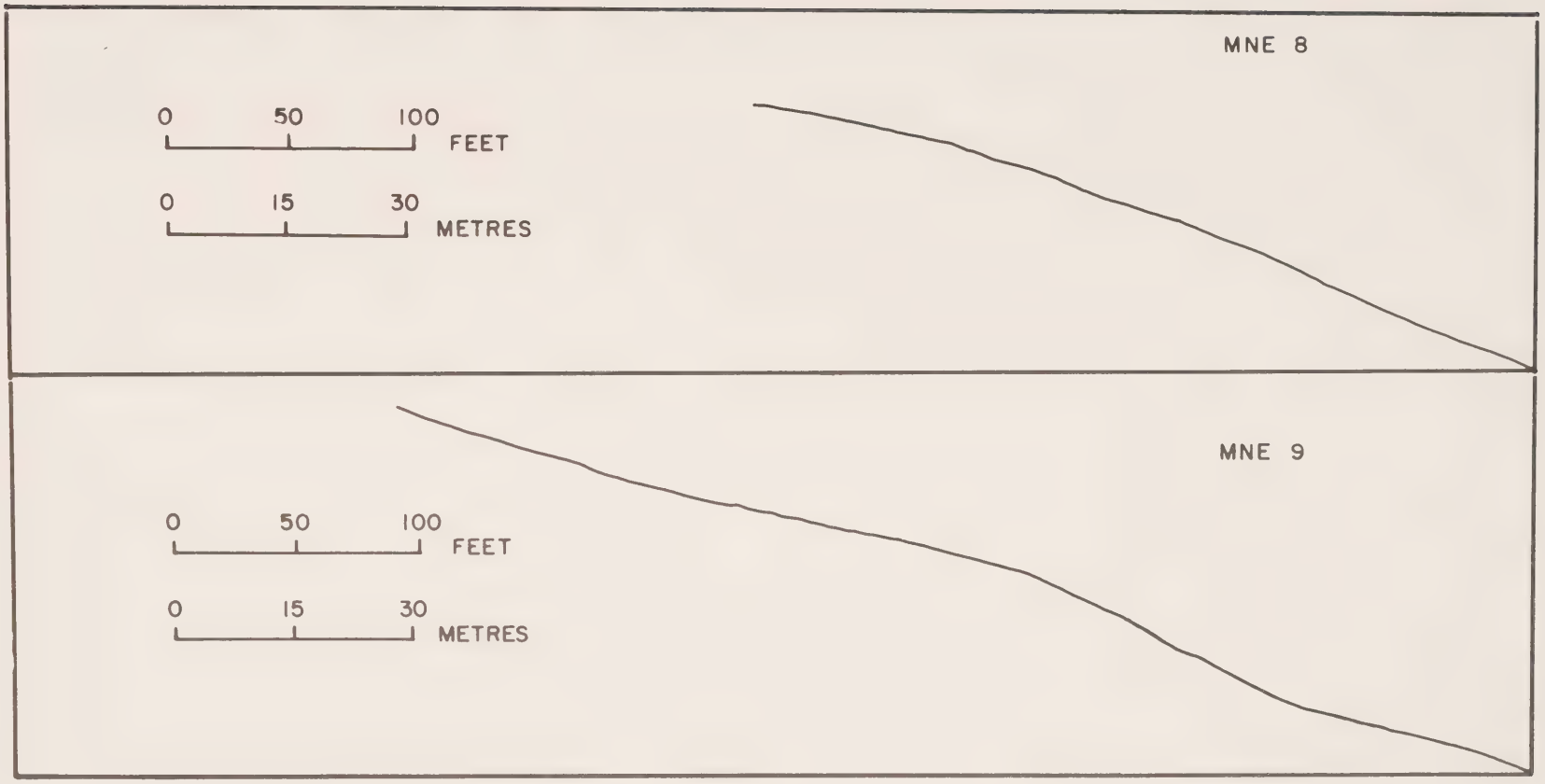


Figure 6. Profiles of retrogressive flow slides.

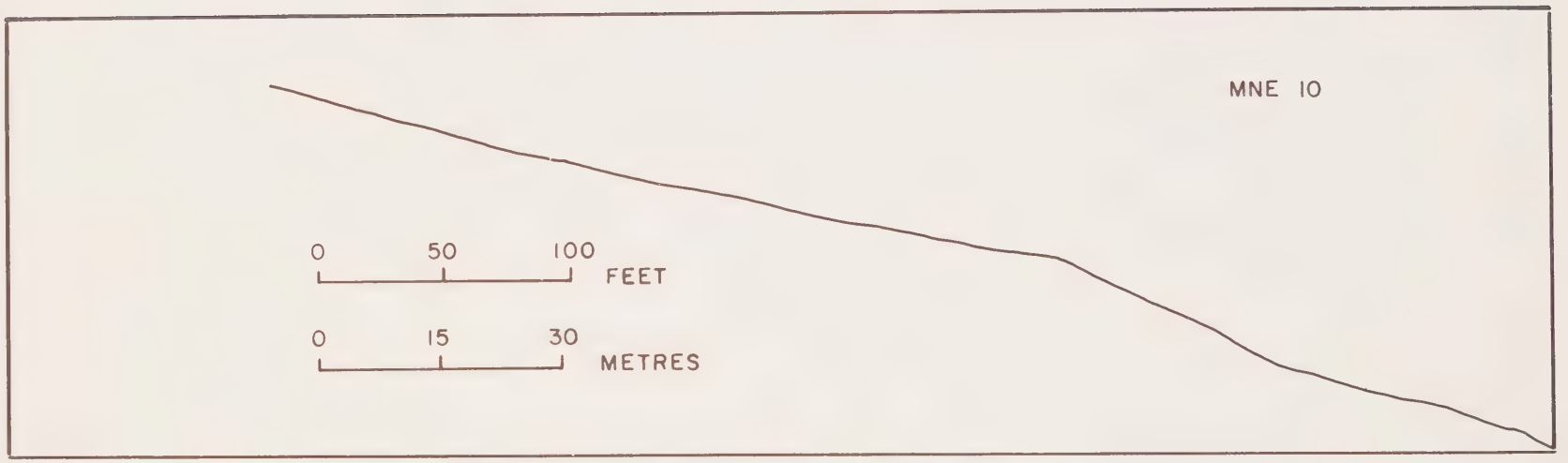


Figure 7. Profile of retrogressive flow slides.

APPENDIX 2.

Figures 8-17. Grain size distribution diagrams.

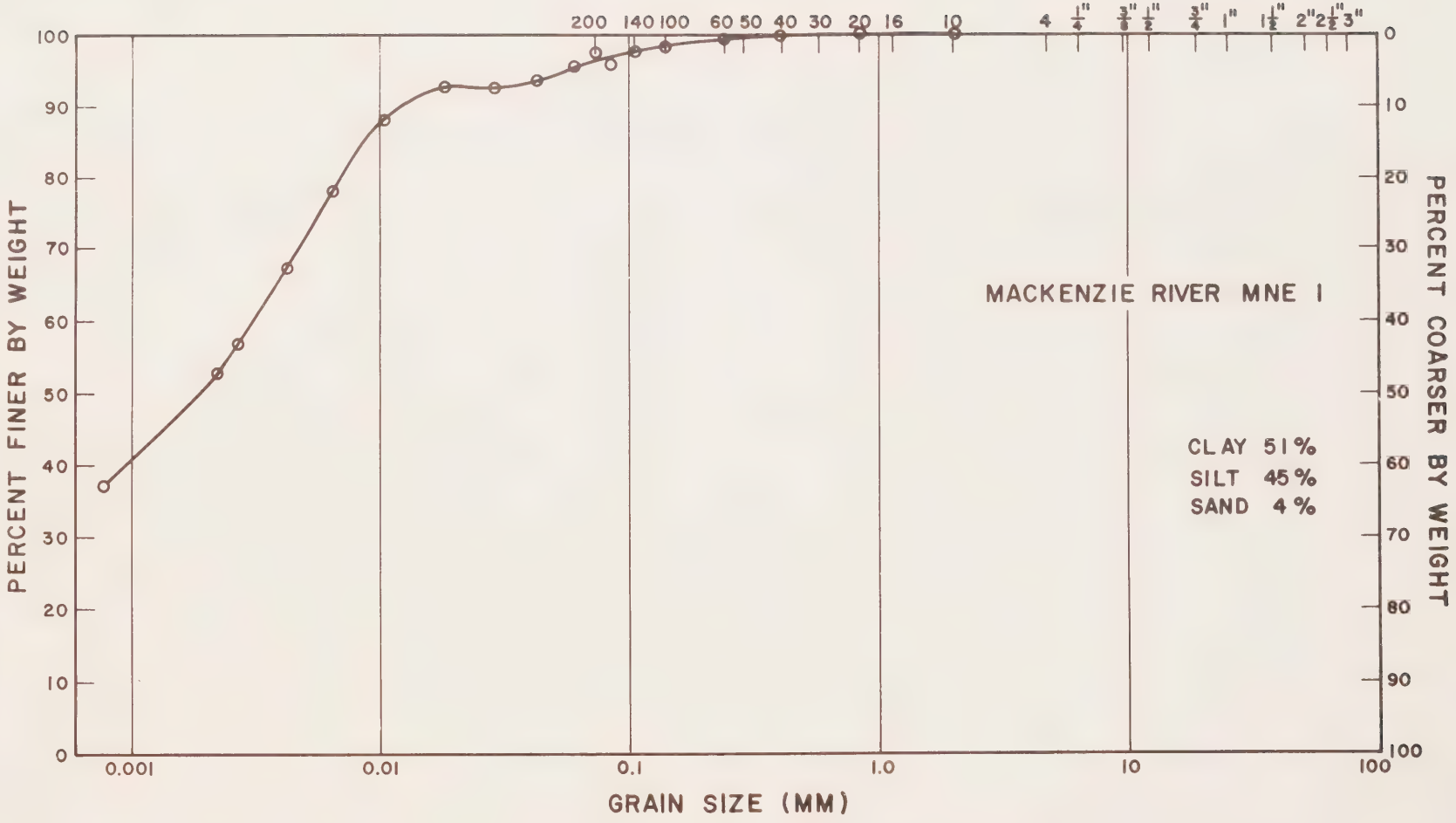


Figure 8. Grain size analysis.

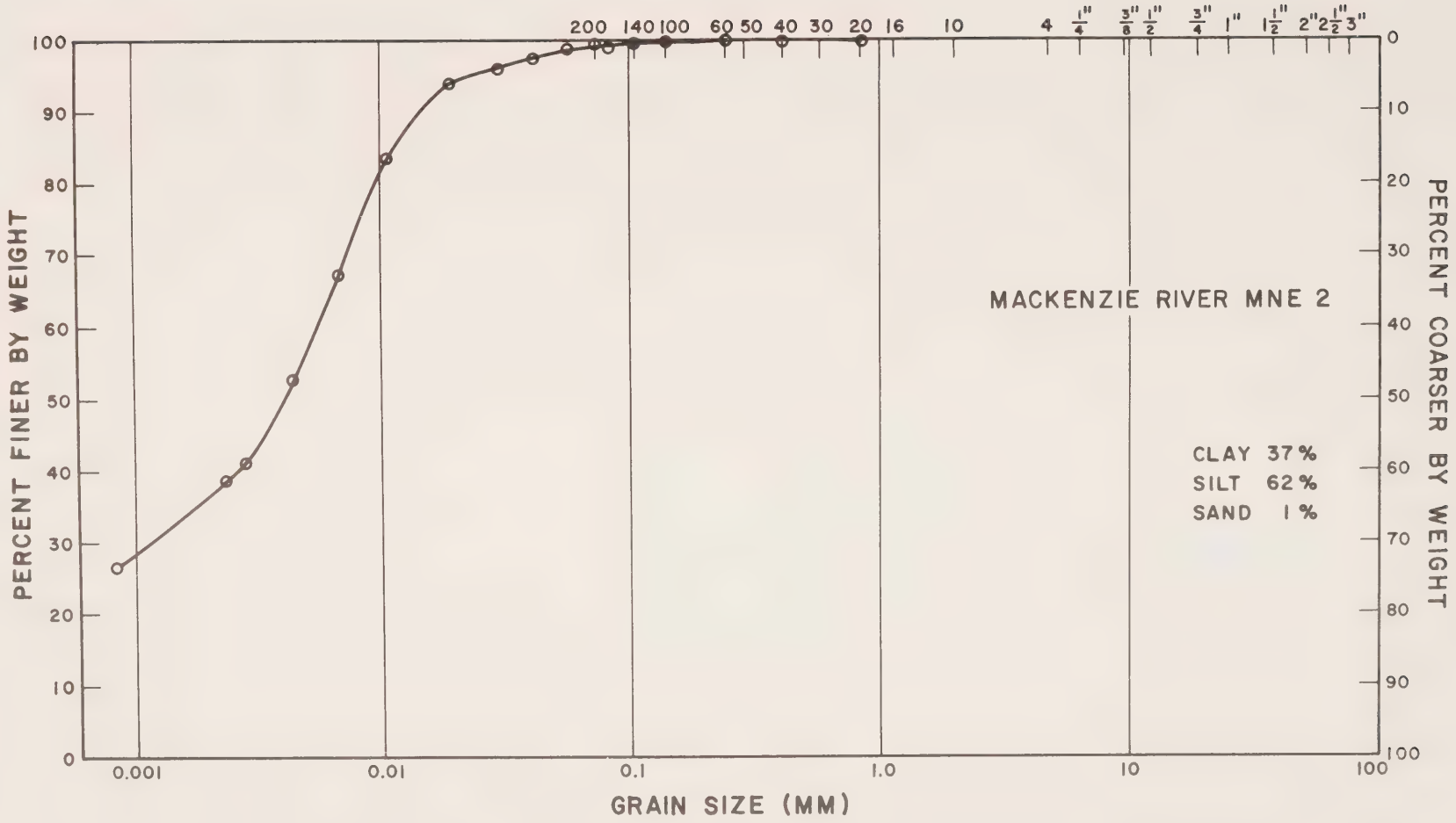


Figure 9. Grain size analysis.

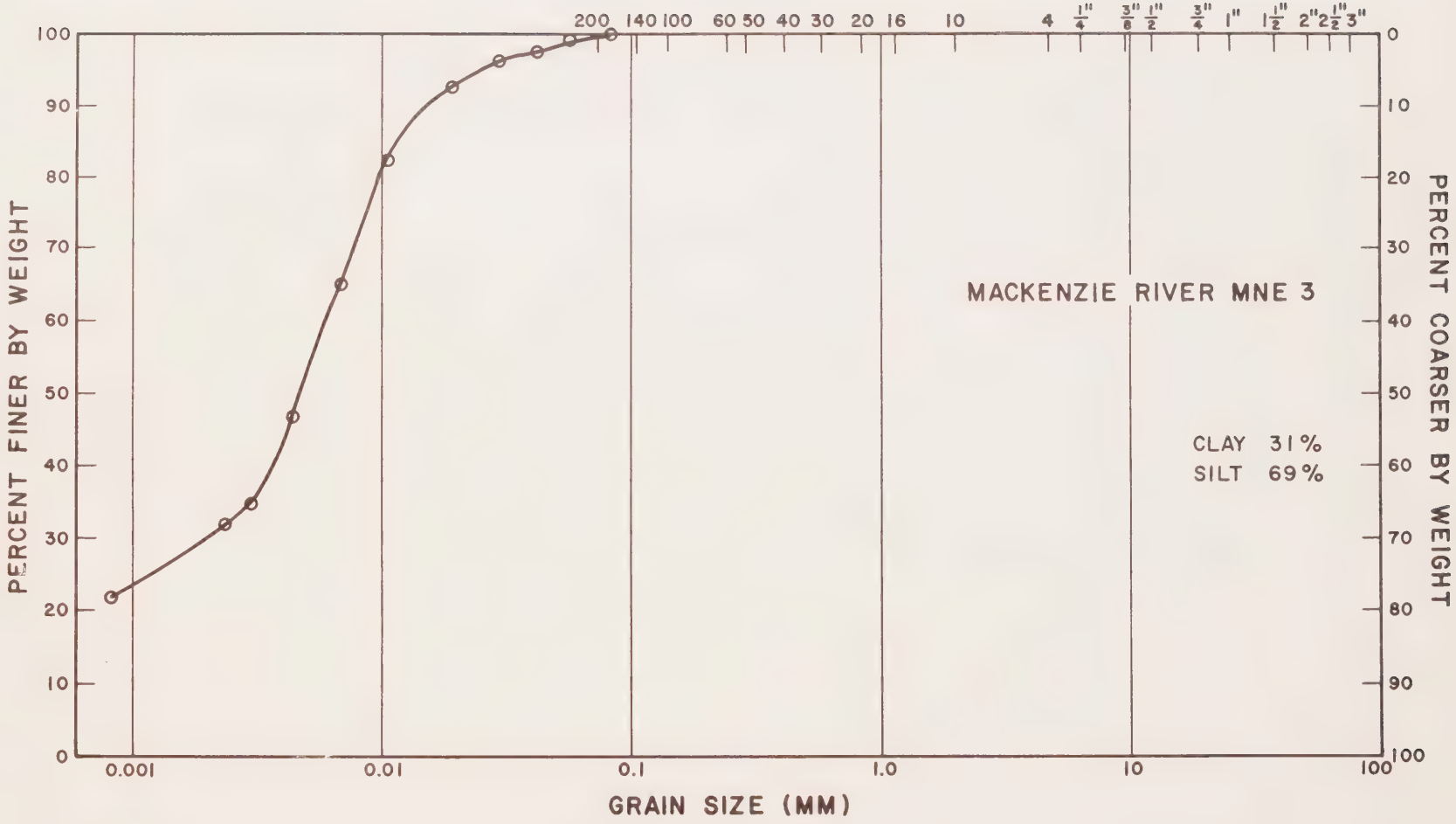


Figure 10. Grain size analysis.

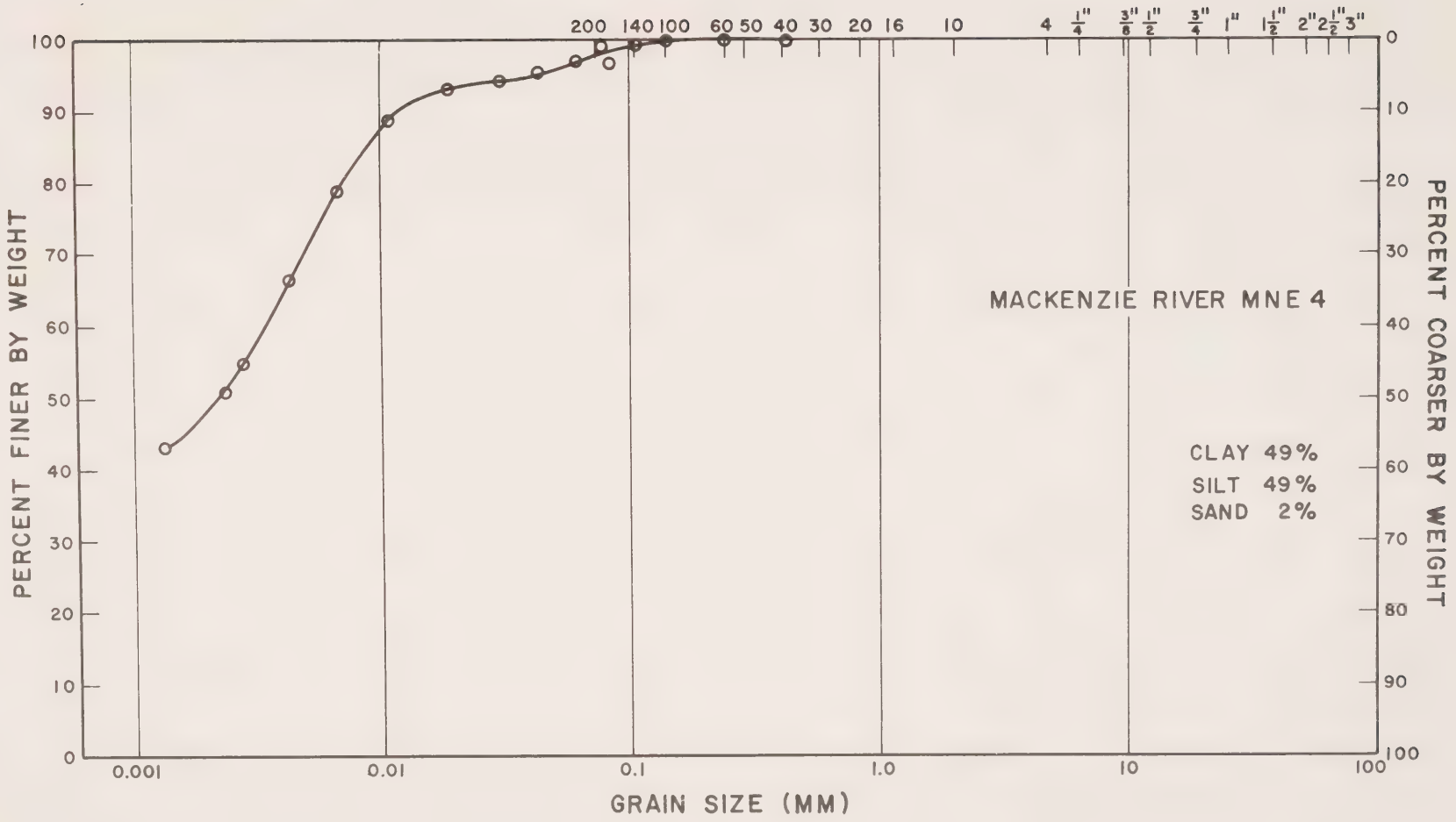


Figure 11. Grain size analysis.

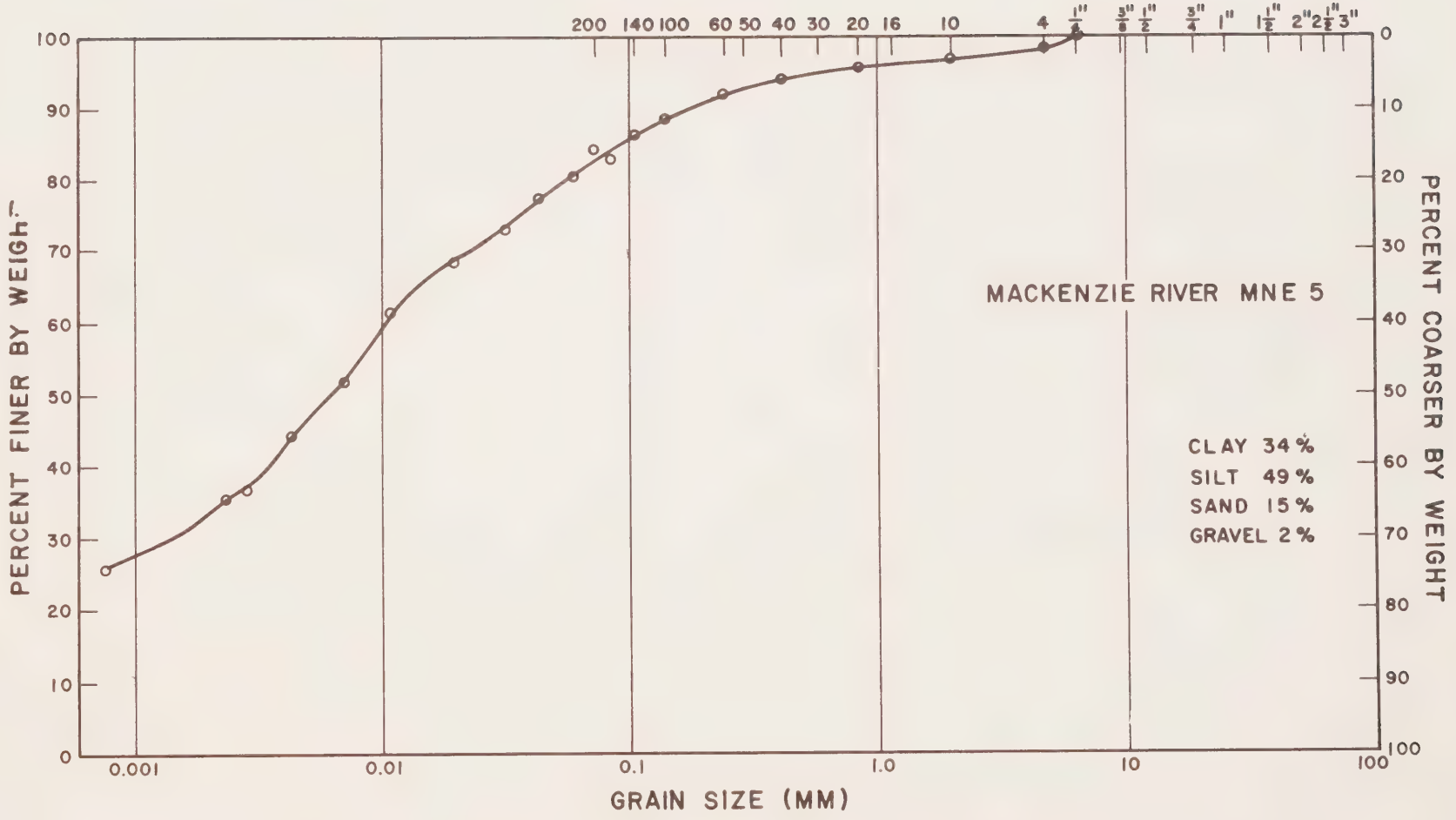


Figure 12. Grain size analysis.

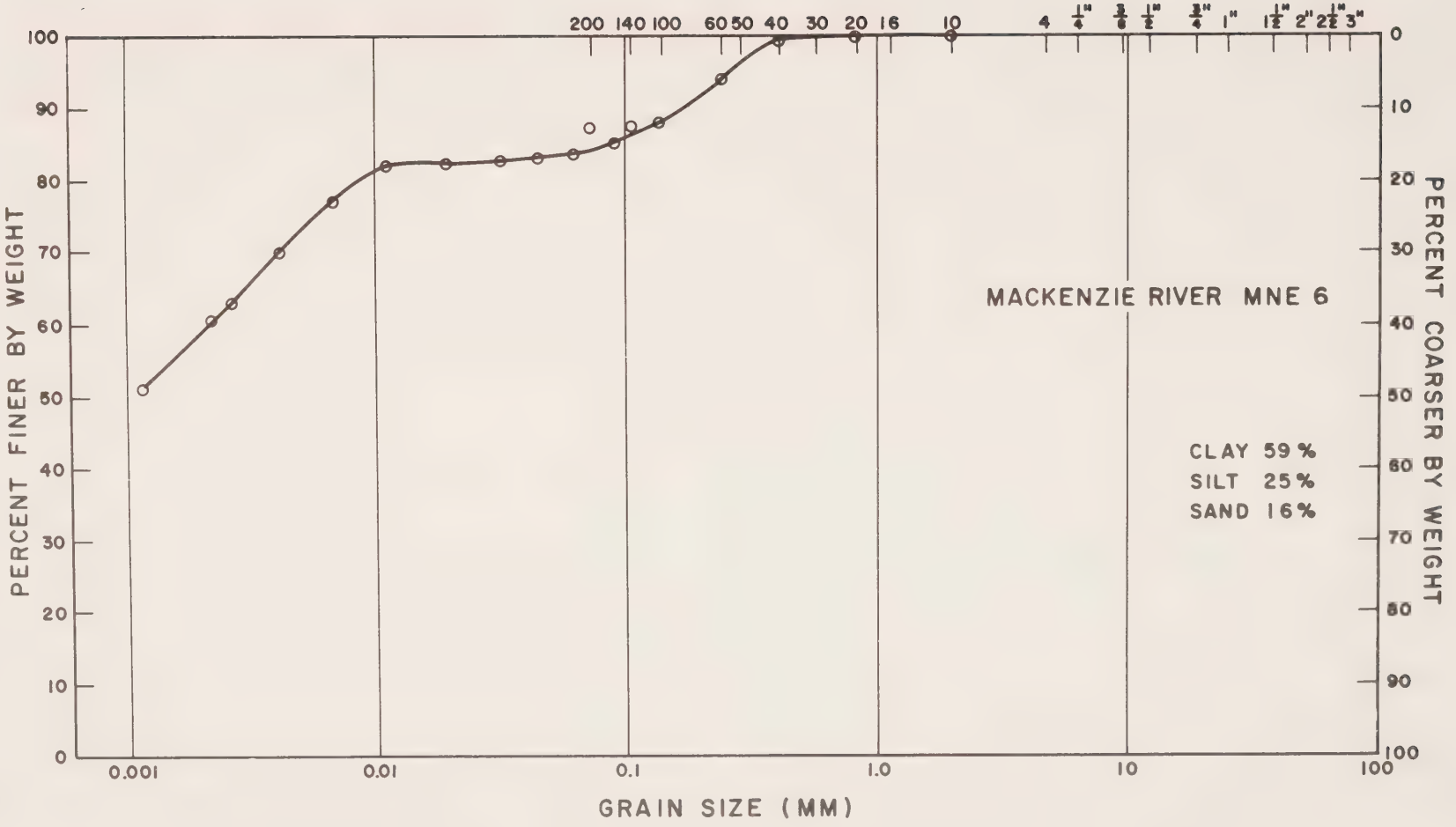


Figure 13. Grain size analysis.

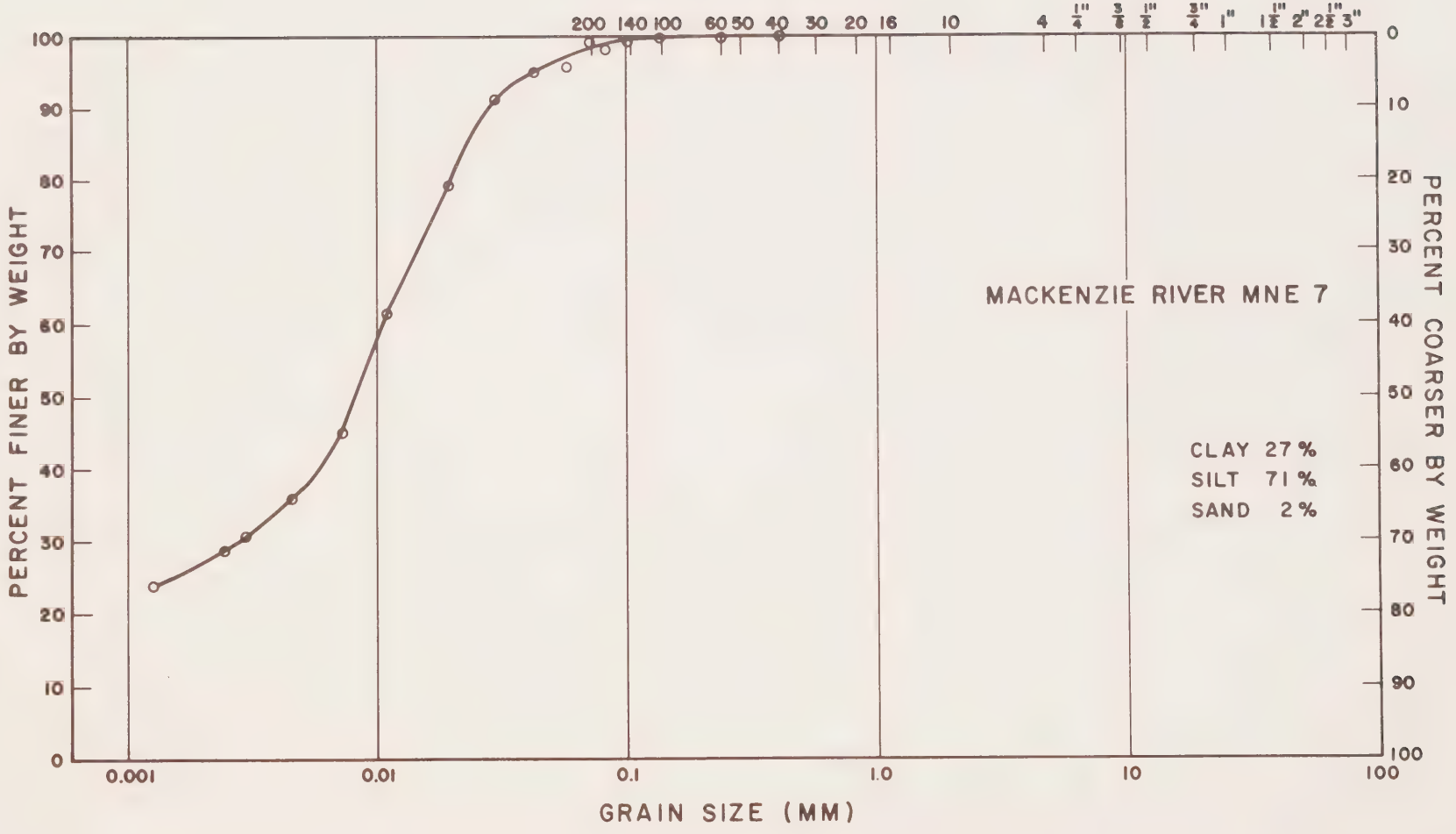


Figure 14. Grain size analysis.

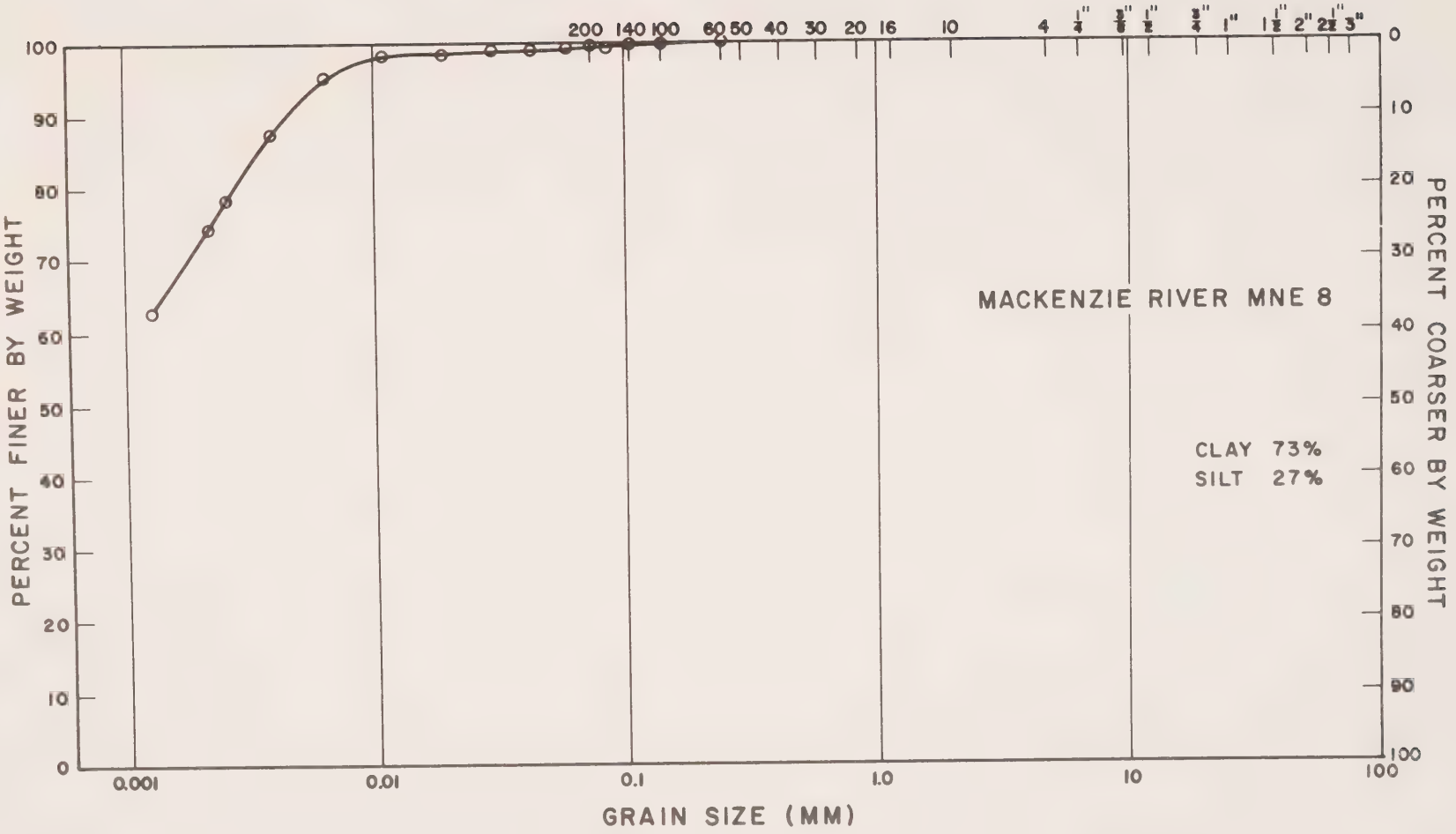


Figure 15. Grain size analysis.

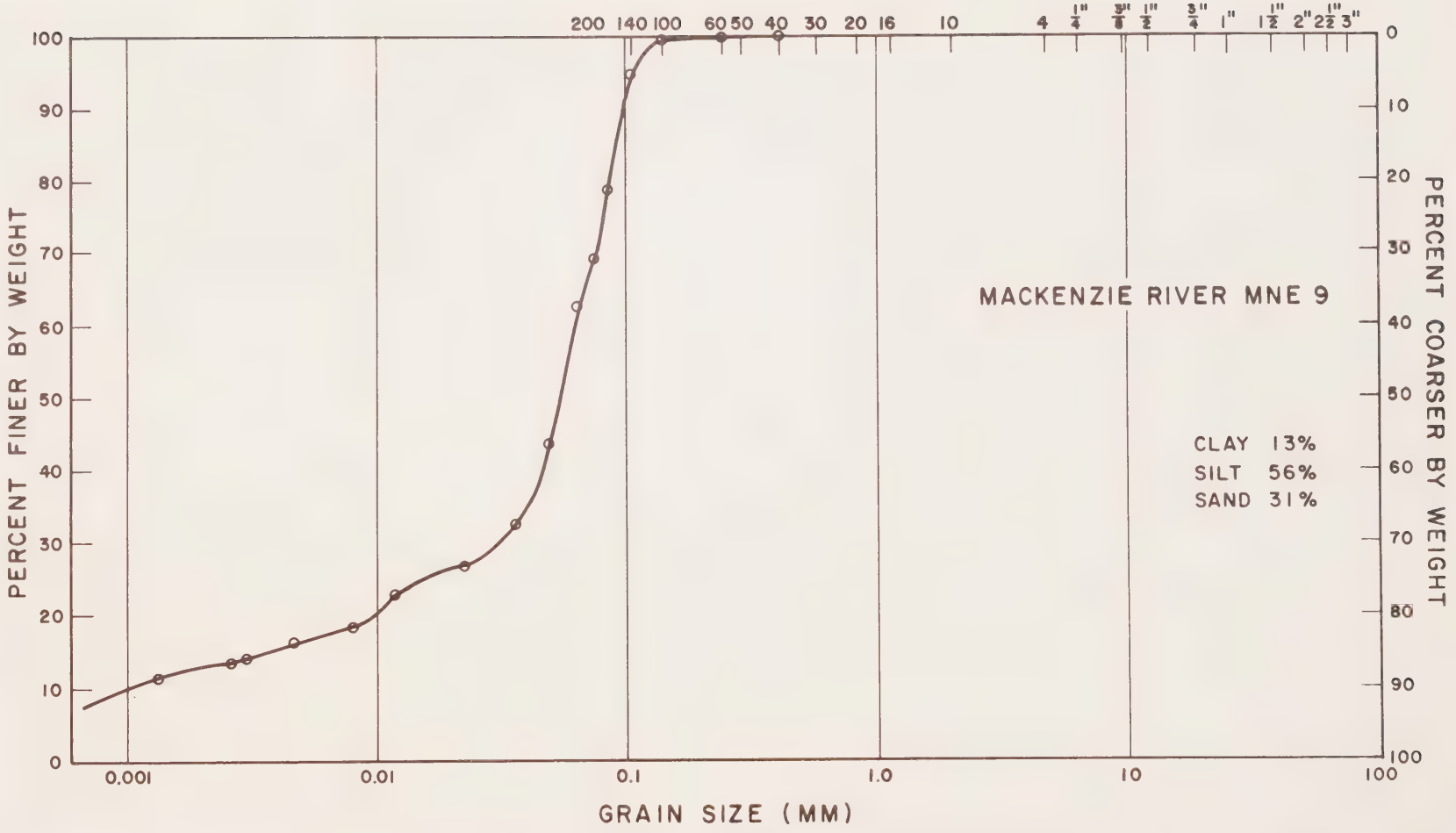


Figure 16. Grain size analysis.

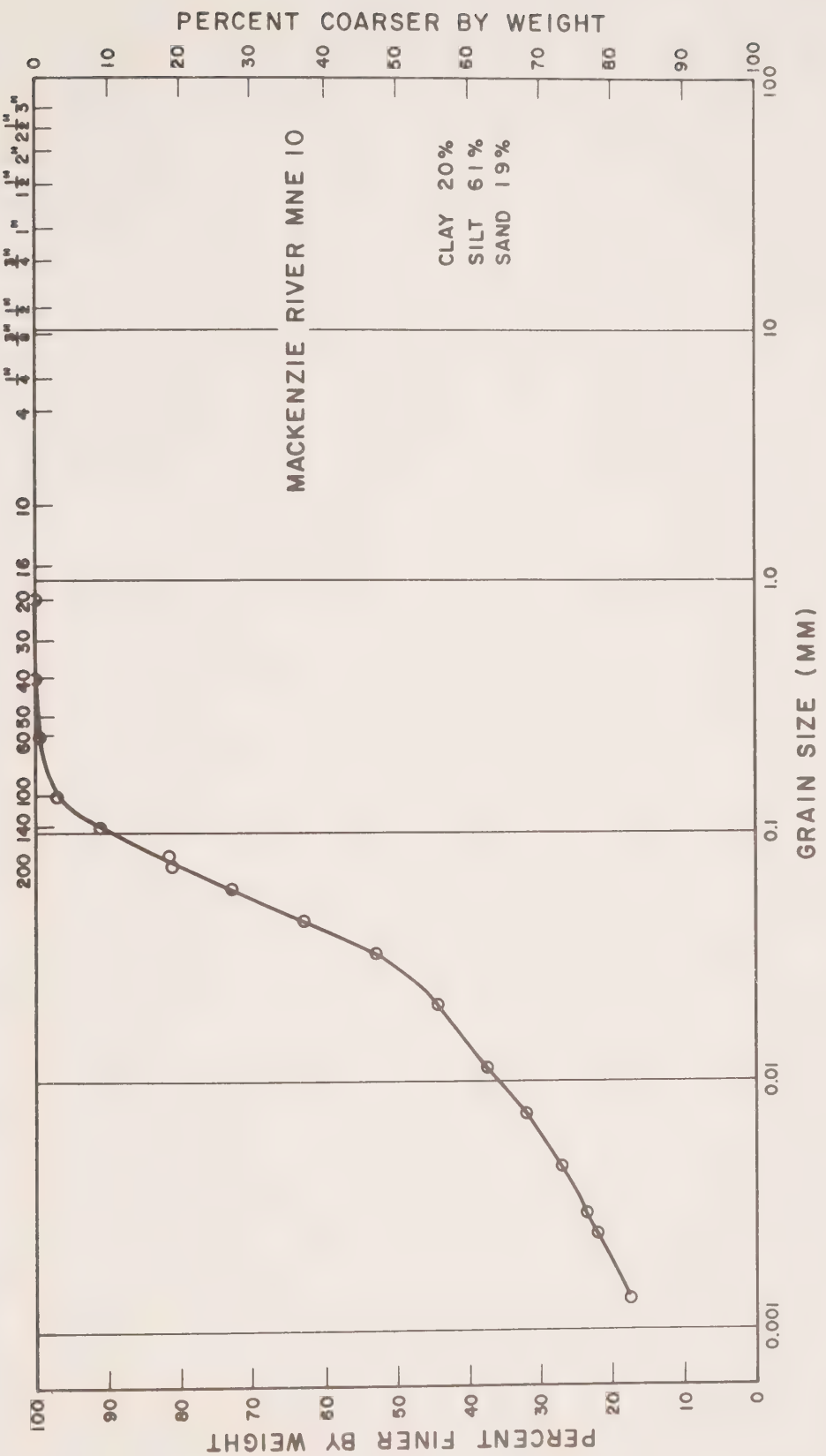


Figure 17. Grain size analysis.

APPENDIX 3.

Figures 18-21. Slope profiles MNES1-S4 and MNWS1-S4.

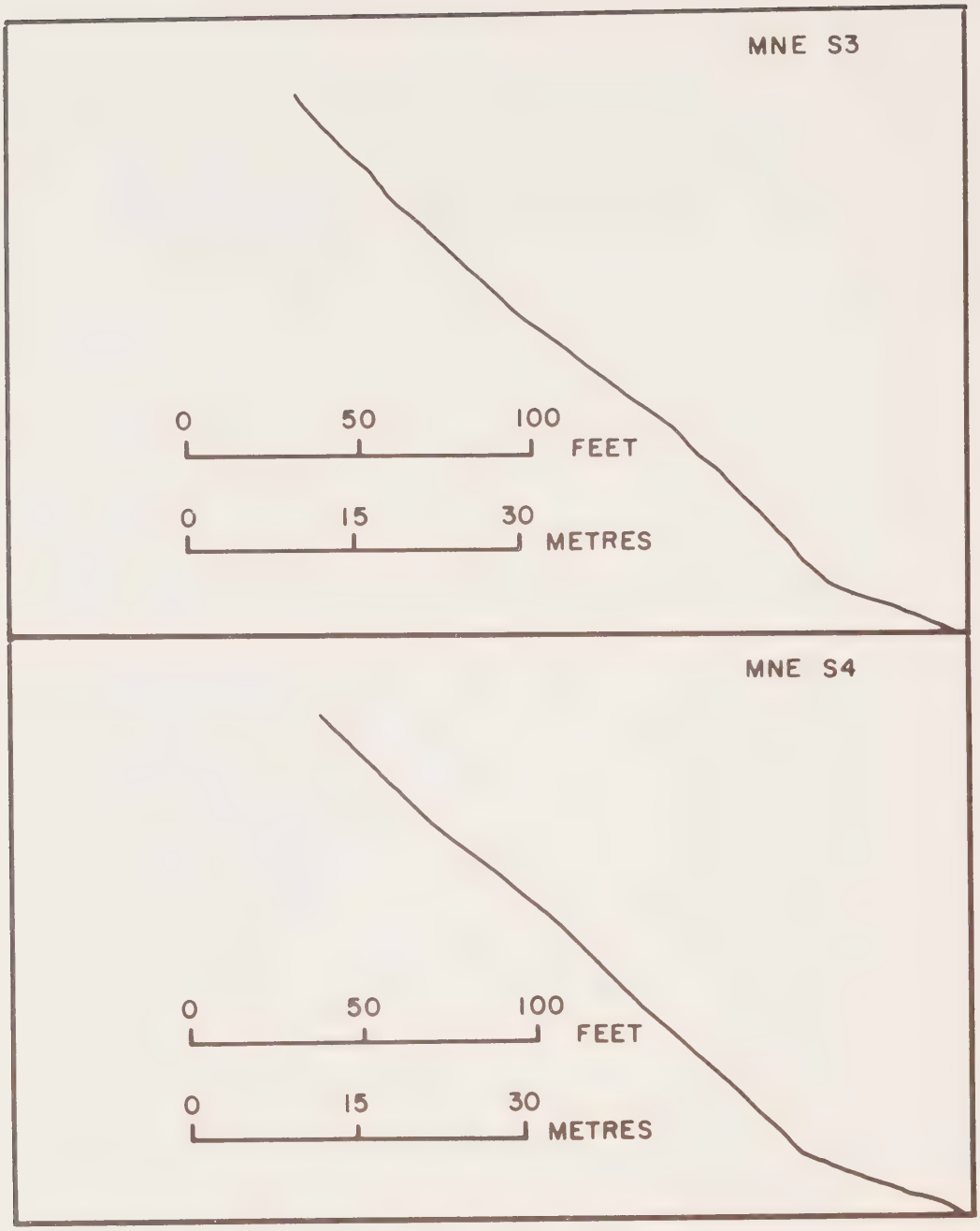


Figure 18. Profiles of steel colluvial slopes.

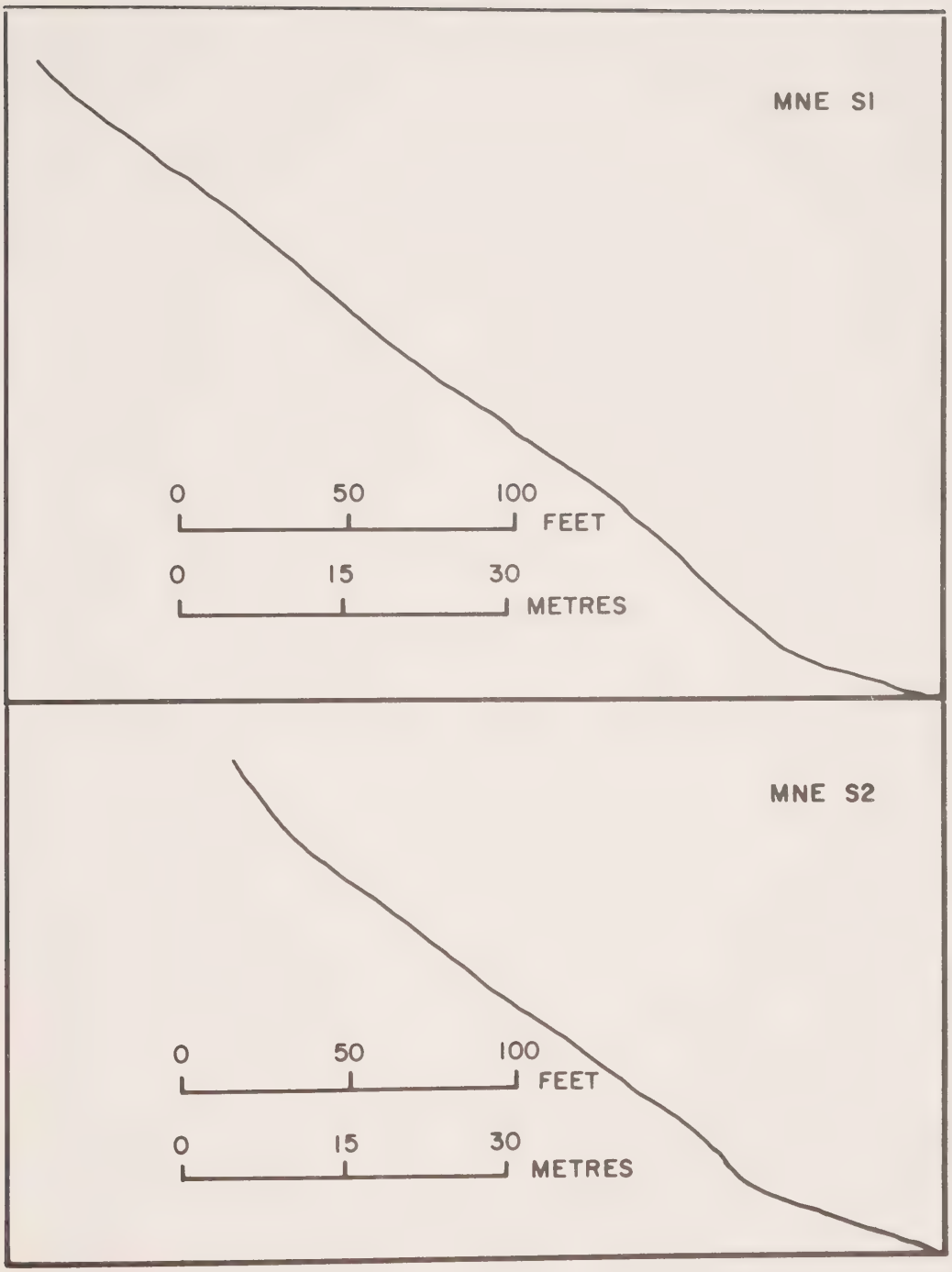


Figure 19. Profiles of steep colluvial slopes.

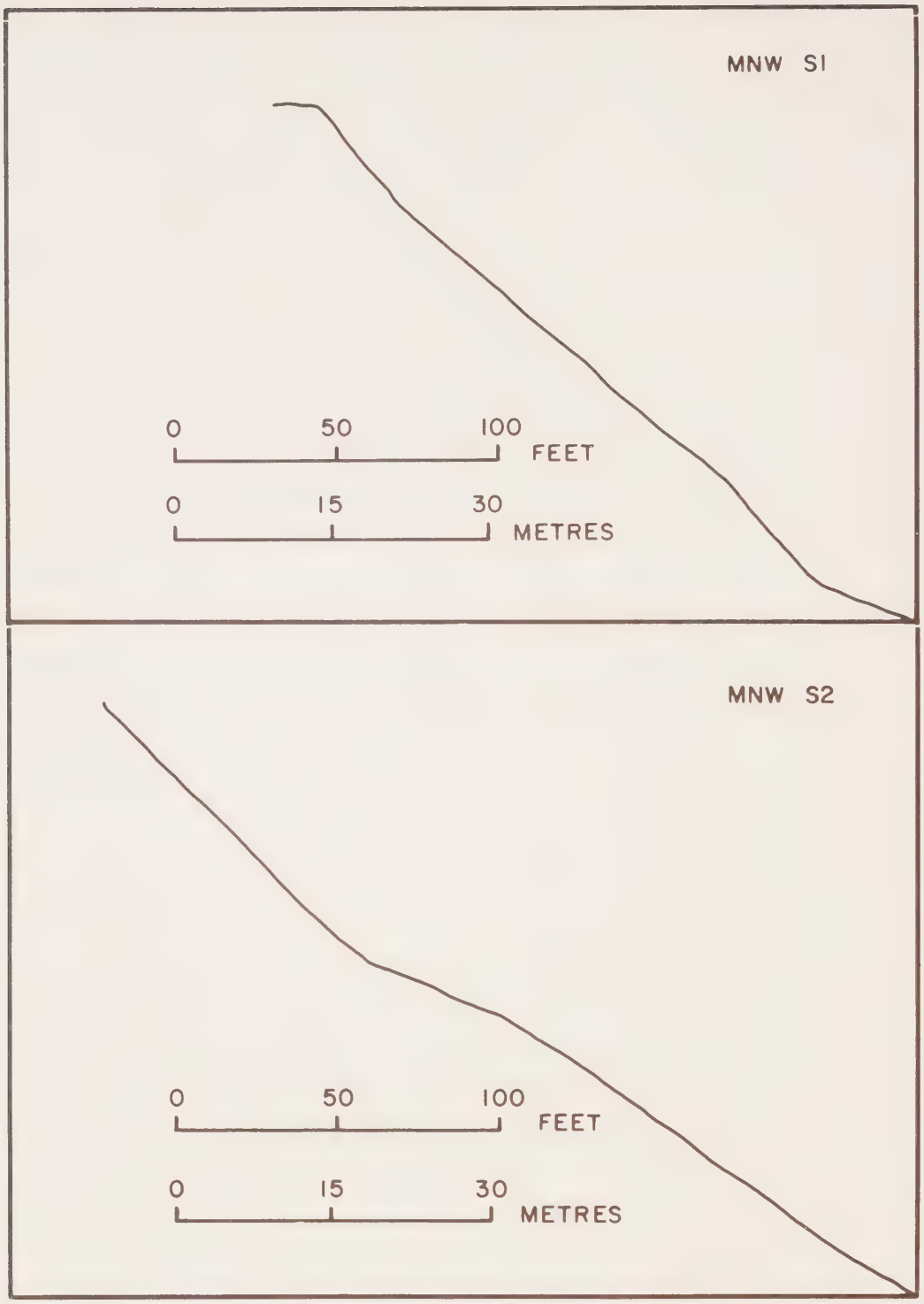


Figure 20. Profiles of steep colluvial slopes.

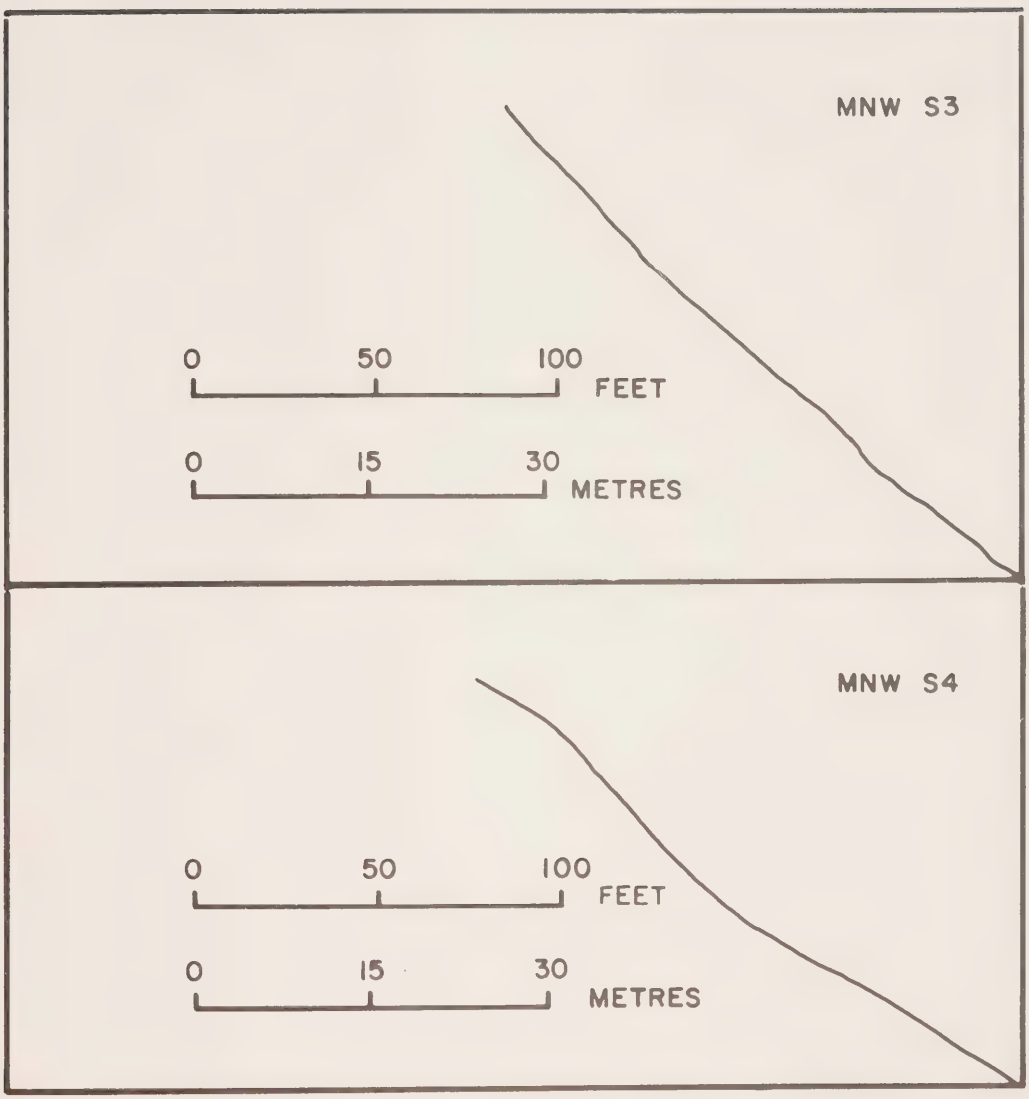


Figure 21. Profiles of steep colluvial slopes.

APPENDIX 4.

Photographs 1-9.



Photo 1. Surficial sloughling of river bank, Liard River.



Photo 2. Mudflow in fire damaged area, glaciolacustrine deposits.



Photo 3. Mudflow in fire damaged area, glaciolacustrine deposits.



Photo 4. Melting permafrost site MNE 1.



Photo 5. Debris tongue site MNE 5. Note bent trees on side of bottleneck.



Photo 6. Mudflow channel at site MNE 1.



Photo 7. Mudflow channel at site MNE 2.



Photo 8. Steep colluvial slope at site MNE S1.



Photo 9. Steep colluvial flow at site MNW S3.

Data (1971)

on

HEIGHT, FREQUENCY OF FLOODS, ICE JAMMING AND TREE-RING STUDIES

by

W. E. S. Henoch

Technical Report 5 To
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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Data on Height, Frequency of Floods, Ice Jamming and Climate from Tree-Ring Studies Part I*

INTRODUCTION

Proposed construction of a pipeline along the Mackenzie River requires data on the disharge of this river and its tributaries, the time of break-up and freeze-up, ice jamming, and time and extent of flooding. The existing data, collected mainly to satisfy the needs of navigation on the Mackenzie River, were made at widely scattered localities, and are of short duration and often lack continuity.

To satisfy some of these requirements a field trip was undertaken in August 1971, to observe indicators of maximum height of former floods and ice jamming on the Mackenzie River between Fort Providence and Fort Simpson and in the Liard River Valley. Increment cores were collected for dendrochronological studies and information on past activities of the river; also to test the inherent tree ring potential as a source for temporal and spatial extension of hydrometric and climatic data.

The use of tree ring data as indices of rainfall, temperature, and riverflow is not new. Good examples of methods for the study of river and slope processes are presented by Senter (1937), Sigafoos (1964), La Marche (1961; 1966; 1968), Helley et al., (1968), and Everitt (1968). Fritts et al. (1971) applied a multi-variate analysis of tree-ring chronologies and derived a series of transfer functions which allowed estimates of anomalous climatic variations.

The decision to apply dendrochronological data to the study of the Mackenzie River was encouraged by the progress made in the development of dendrochronological techniques (Parker, 1970, 1972). The routine procedure used to produce dendrochronological data by X-ray densitometry is shown in Appendix 1.

Only a few dendrochronological studies have been made in the areas of the Mackenzie Basin. Giddings (1947) gave white spruce chronology for the Mackenzie Delta and found a positive correlation between tree-ring widths and mean July temperatures recorded in Aklavik. Heginbottom (Geological Survey of Canada) has studied changes in vegetation and geomorphic processes in the lower Mackenzie Basin; and Morland (National Museum of Canada) collected increment cores for archaeological studies. Increment cores collected by these scientists are to be processed on completion of the tree-ring analysis at the Dendrochronological Laboratory, Vancouver, B.C.

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* Part 2. Parker, M.L., 1972. Progress Report on Dendrochronological Studies of the Mackenzie and Liard River Valleys Tree-ring Samples by X-Ray Densitometry. Report prepared for the Glaciology Division, Inland Waters Directorate, Ottawa, Ontario. The report contains master chronology from 1740 to 1971, based on maximum tree-ring density.

INDICATORS OF THE MAXIMUM HEIGHT OF FLOOD AND ICE JAMMING

For the purpose of river crossings by any construction it is necessary to know the maximum level and the frequency of floods and ice jamming in a given reach of the river. To obtain these data maximum height of driftwood, flood silt deposits, ice injury to trees, and the height of ice-shove ridges were measured barometrically.

The elevation of marks left by floods and river-ice has been measured barometrically from the river level (a.r.l.), as the use of any other datum was not practical. Elevation data given are therefore relative, not absolute, values. The Liard River level can vary in different reaches of the river between high flood levels at spring time and low levels in autumn by 2 - 3 m. The relative values are sufficient to indicate the areas susceptible to catastrophic flooding.

Driftwood indicates the level of flooding which could have occurred anytime from break-up to freeze-up and the level to which the river was ponded behind an ice jam.

Injuries to the bark of trees growing on the banks of the river are frequently caused by the ice carried by flood waters. The injuries usually heal over, but they can be identified and dated by dendrochronological analysis. Field experience has shown that for the study of ice injuries to trees, whole cross-sections of trees are required rather than increment cores, because the latter give only a limited amount of information about the scars.

Where the flow of the ice is free, the height of the injury to trees or the height at which the ice rafts are deposited indicate also the height of flooding. However, where the flow of ice is hindered by a bend in the river or an island, ice rafts are pushed onto the banks and plough up the dirt into ice-shoved ridges high above flood levels. Further in this report, illustrations show ice-shoved ridges reaching 9.5 m, although flood water levels are only 2 m above river level.

Ice jams, caused by accumulated ice, restrict the flow of the whole river and cause ponding of the river behind the ice jam. In these circumstances the maximum level of flooding is close to the height of the ice jam. Ice jams usually occur at break-up, but it is known that, in some years, ice flows coming from Great Slave Lake accumulate and build an ice jam at Fort Providence at the time of freeze-up.

Ice jams affect not only the banks of the rivers but also their floor. The damage that can be done to any construction can be illustrated by the history of the submarine telephone cable at Fort Providence. The first cable across the Mackenzie River was broken at the time of the first break-up after the cable was laid. Consequently the new telephone cable was suspended high above the river.

FIELD RECONNAISSANCE

During the summer of 1971 - 19 July to 6 August - a reconnaissance trip was made from Fort Providence down the Mackenzie River to Fort Simpson and

up the Liard River and its tributary, the South Nahanni River, to Hot Springs. The author and a student assistant travelled the route.

The main area of this reconnaissance study was the Liard River from its mouth to its confluence with the South Nahanni River. The Mackenzie River section of the reconnaissance was undertaken only to reach the Liard River but observations on flooding and ice jamming, and increment cores were taken where possible.

During the trip 195 increment cores of various tree species were collected. The preliminary examination of increment cores has shown that no old trees likely to provide long chronologies were found. This is the result of frequent forest fires and comparatively short physiologic cycle of trees in the area. Tall trees of large diameter were reported to grow near Hot Springs but it was found that they are not very old. The oldest trees sampled were 231 years old, growing on the left bank of Liard River opposite Nahanni Butte.

In addition to obtaining information on the maximum height and frequency of flooding and ice jamming, master chronologies have been established and the value of these chronologies tested for spatial and temporal extension of climatological and hydrological data.

The location of the sites where the observations of former flood levels were made and increment cores were taken is shown in Figures 1 and 2. Data pertinent to each site where increment cores were taken are shown in Table 1. The distance of the sites on the Mackenzie River is measured from Fort Providence, and on the Liard River from Fort Simpson.

Dendroclimatological data

Statistical tests have shown positive correlation between the maximum ring density of 13 cores of white spruce found on the bank of the Liard River, and August mean maximum temperature (Fig. 3) at Fort Simpson, N.W.T., for the years 1928-1970. The results are in agreement with earlier findings (Giddings, 1947; Parker and Henoch, 1971).

THE MACKENZIE RIVER FROM FORT PROVIDENCE TO FORT SIMPSON

Mackenzie River discharge, freeze-up, and break-up data have been analyzed by J.R. Mackay (1963) and D.K. MacKay (1967), D.K. MacKay and J.R. Mackay (1972).

The break-up in Fort Providence is usually completed in the third week of May and the freeze-up in the first days of December. Ice jamming may occur both at the time of break-up and freeze-up and is most severe between Providence Island and the north shore of the Mackenzie River. The action of river ice leaves ice-shoved ridges on the banks of the river and on the shores of the islands. The ice-shoved ridges are formed by ice floes mainly during the break-up and attain their greatest dimensions between Fort Providence and Mills Lake, reaching their highest elevations on the upstream shores of islands.

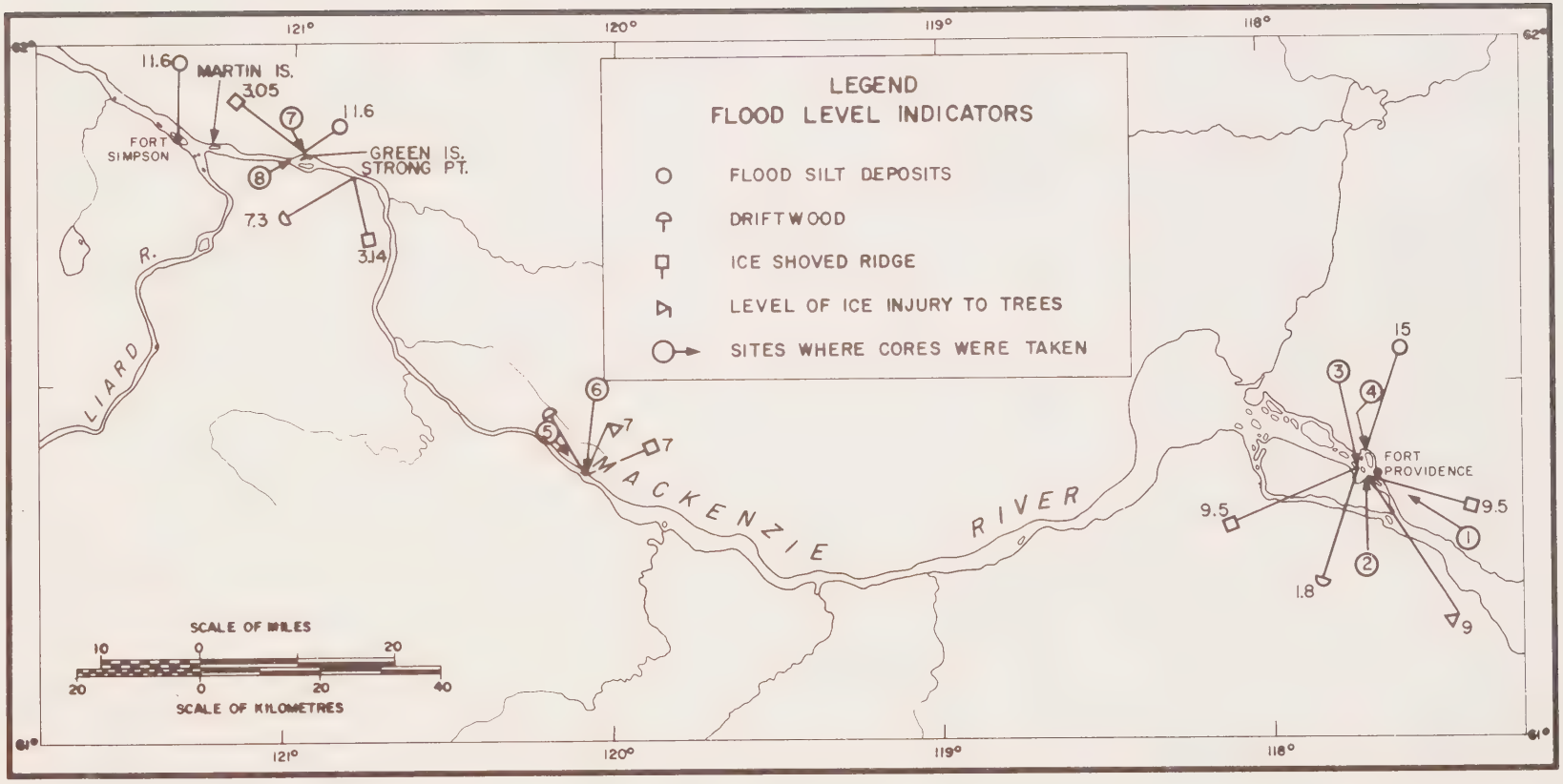


Figure 1. Mackenzie River, site locations of maximum height of floods. Location of indicators above river level, July-August, 1971.

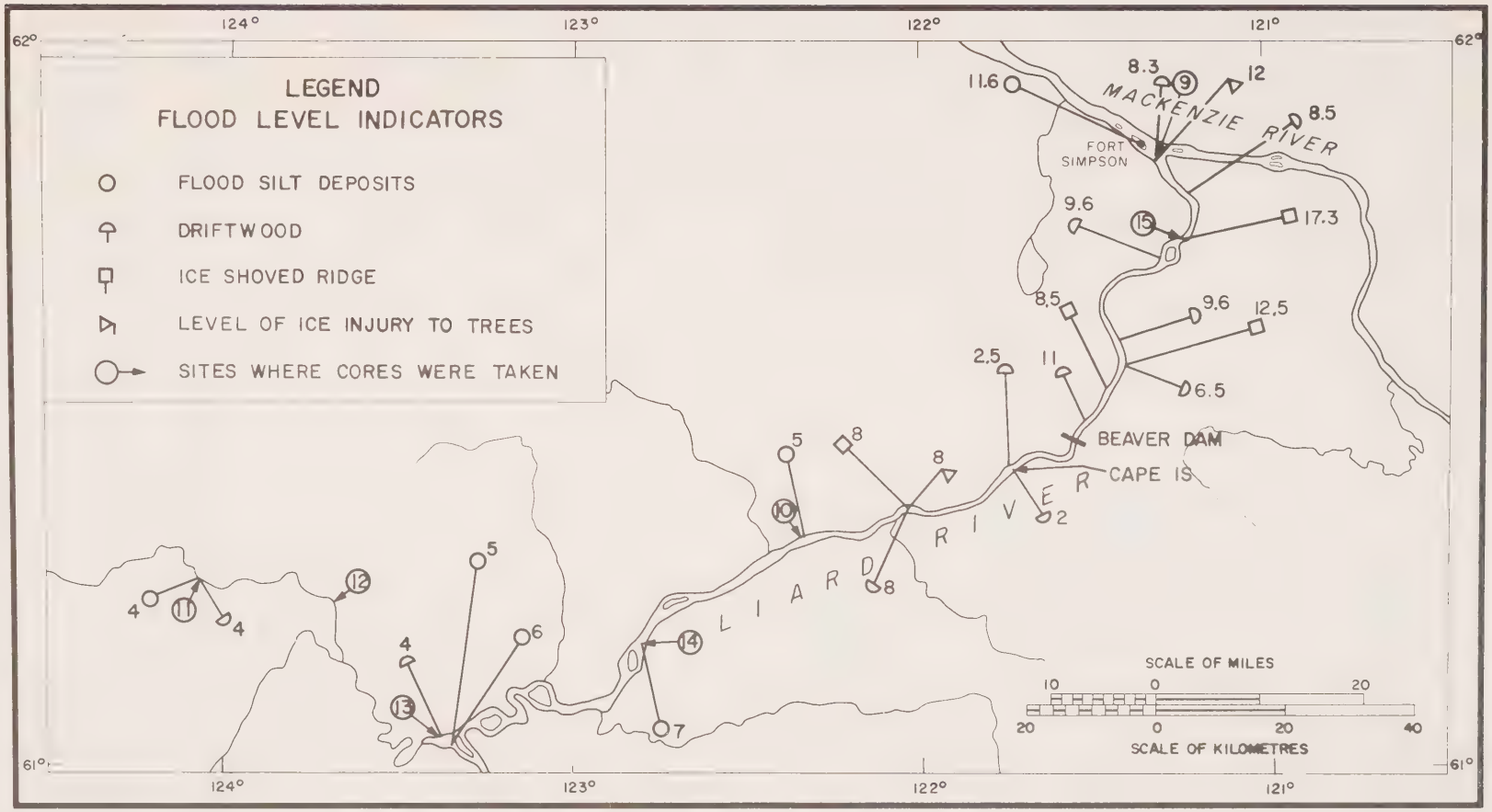


Figure 2. Liard River, site locations of maximum height of floods. Location of indicators above river level, July-August, 1971.

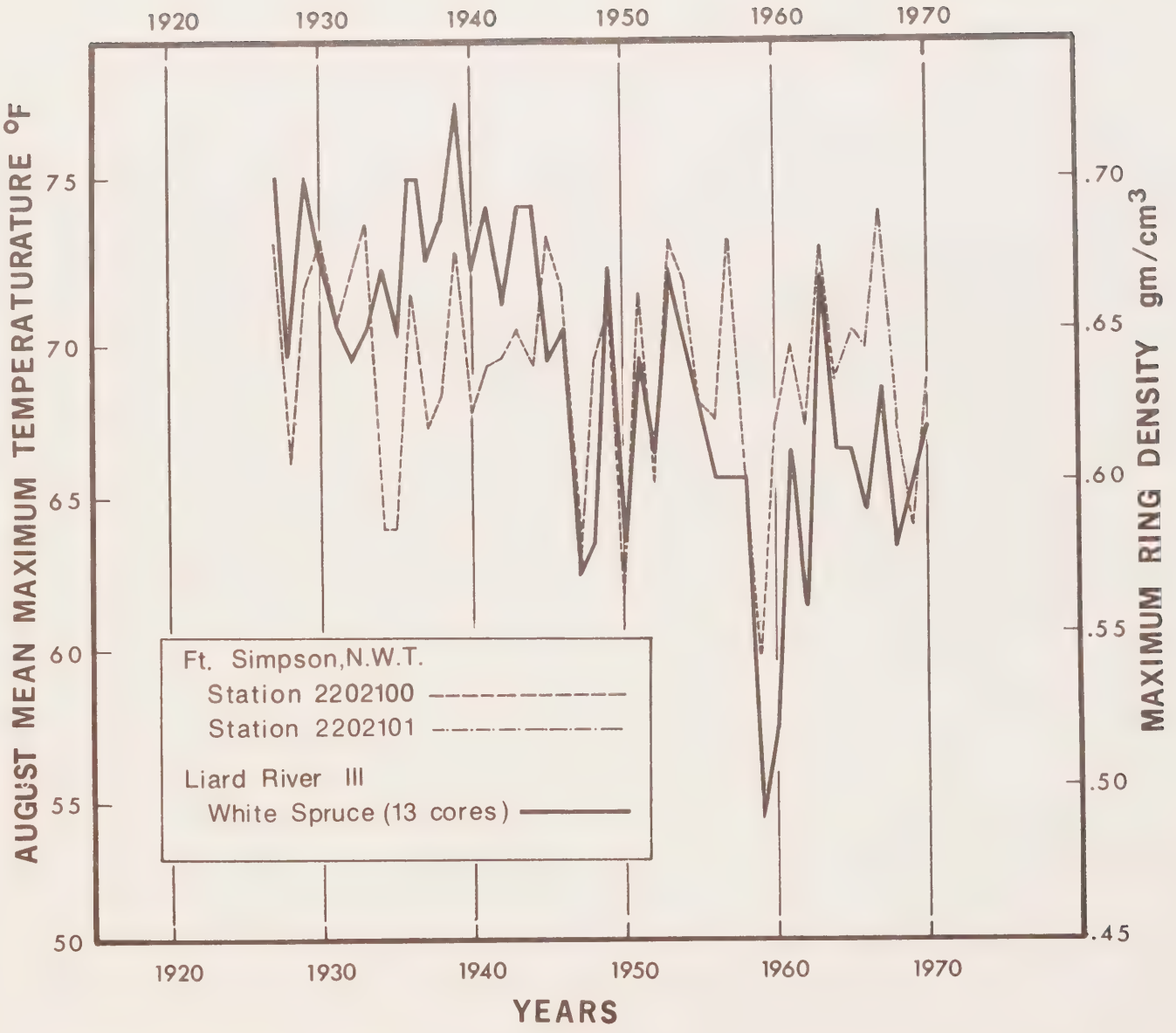


Figure 3. Correlation between maximum ring density of 13 white spruce cores from

Table 1. Data on tree increment cores collected in 1971

SITE	DATE	INCREMENT CORE NO. (P S W H 71) CORE NO.	INCREMENT CORE NO. (P S W H 71) NO. OF CORES	TREE SPECIES: WHITE SPRUCE	TREE SPECIES: POPLAR	TREE SPECIES: BIRCH	TREE SPECIES: OTHERS	SITE LOCATION GEOGR. CO-ORDINATES	SITE ELEVATION ABOVE RIVER LEVEL m	HEIGHT (m) (Above River Level): HIGH WATER MARK: DRIFTWOOD	HEIGHT (m) (Above River Level): HIGH WATER MARK: SILT DEPOSITS	HEIGHT (m) (Above River Level): RIVER-ICE MARKS: TREE INJURY	HEIGHT (m) (Above River Level): RIVER-ICE MARKS: ICE SHOVE RIDGES	REMARKS
1	20/7		10	10				W side of road 7.5 km E of FORT PROVIDENCE						Exploratory cores
2	22/7	1 to 4	4	4				Small island S of GREEN ISLAND 3 km W of FORT PROVIDENCE 61 21'42" 117 41'58"				9	9.5	Upstream bank
3	22/7	5 to 12	17	17				South shore GREEN ISLAND 61 21'48" 117 41'55"	10	1.8			9.5	Terrace
4	23/7	13 to 23	19	16	2	1		Rt. bank of Mackenzie River nr. abandoned Indian village 61 23'30" 117 43'00"	2-2.5	1.5				High-water marks 1.5 m increment core No. 21, birch.
5	25/7	25	1	1			1	CACHE ISLAND 61 22'30" 120 05'00"		2			7	Leaning tree on W promontory of island's receding slope
6	25/7	26	3	3				CACHE ISLAND 61 22'30" 120 05'00"				7		Upstream bank

Table 1 cont'd.

SITE	DATE	INCREMENT CORE NO. (P S W H 71) CORE NO.	INCREMENT CORE NO. (P S W H 71) NO. OF CORES	TREE SPECIES: WHITE SPRUCE	TREE SPECIES: POPLAR	TREE SPECIES: BIRCH	TREE SPECIES: OTHERS	SITE LOCATION GEOGR. CO-ORDINATES	SITE ELEVATION ABOVE RIVER LEVEL m	HEIGHT (m) (Above River Level): HIGH WATER MARK: DRIFTWOOD	HEIGHT (m) (Above River Level): HIGH WATER MARK: SILT DEPOSITS	HEIGHT (m) (Above River Level): RIVER-ICE MARKS: TREE INJURY	HEIGHT (m) (Above River Level): RIVER-ICE MARKS: ICE SHOVE RIDGES	REMARKS
7	26/7	27	3		3			MACKENZIE RIVER Terrace N of GREEN ISLAND 61 50'55" 120 57'30"		9.5		11.5	5.5	14-18 m terrace
8	26/7	28 to 39	23	18	5			MACKENZIE RIVER Terrace N of GREEN ISLAND 61 50'55" 120 57'30"	14					14-15 m terrace
9	29/7	41 to 44	4		4			Mouth of LIARD RIVER 61 50'05" 121 19'05"		8.3		12		18 m terrace
10	30/7	44 to 53	18	17	1			Island 5.5 km E of mouth MATOU RIVER 61 19'15" 122 02'50"	9-10	5				
11	2/8	54 to 73	36	27	9			SOUTH NAHANNI RIVER HOT SPRINGS 61 15'00" 124 02'50"		4	4			No. 67 Leaning tree on the edge of undercut terrace 5m a.r.l.

Table 1 cont'd.

SITE	DATE 1971	INCREMENT CORE NO (P S W H 71) CORE NO.	INCREMENT CORE NO (P S W H 71) NO. OF CORES	TREE SPECIES: WHITE SPRUCE	TREE SPECIES: POPLAR	TREE SPECIES: BIRCH	TREE SPECIES: OTHERS	SITE LOCATION GEOGR. CO-ORDINATES	SITE ELEVATION ABOVE RIVER LEVEL m	HEIGHT (m) (Above River Level): HIGH WATER MARK: DRIFTWOOD	HEIGHT (m): HIGH WATER MARK: SILT DEPOSITS	HEIGHT (m): RIVER-ICE MARKS: TREE INJURY	HEIGHT (m): RIVER-ICE MARKS: ICE SHOVE RIDGES	REMARKS
12	2/8	74 to 83	10	10				Left bank South NAHANNI 2.5 km E of YOHIN RIDGE 61 15'20" 123 47'55"	2		2			Flood terrace
13	3/8	84 to 94	20	19		1		Island opposite NAHANNI BUTTE 61 02'45" 123 22'30"	5	4				
14	4/8	95 to 105	26	26				Island 12.07 km E of BLACKSTONE River	7		7			
15	5/8	106 to 111	5	5				Right bank of LIARD RIVER below the ferry 61 42'50" 121 13'45"	16				17.3	Terrace
TOTAL		195												

Figure 4 shows a schematic profile of the upstream shore of a small island near Fort Providence, just south of Green Island. Ice-shoved ridges have formed to a height of 9.5 m, that is, 0.5 m higher than the island's forest floor.



Fig. 4. Indications of river-ice action on a small island near Fort Providence (Site 2, Table 1).

Ice scarring was found on two white spruce trees behind ice-shoved ridges. The scars were 9 m a.r.1. Increment cores were taken below and through each scar. Analysis of X-ray photographs of these increment cores (Appendix 2, Site No. 2, cores: PSWH71-1E, PSWH-71-1, PSWH-71-2E, and PSWH71-2) indicates that the trees were injured by ice probably between the 1969 and 1970 growing season.

On Green Island (5.2 km west from Fort Providence) ice-shoved ridges reached the height of 9.5 m. The forest floor, at 10 m a.r.1., showed no signs of recent flooding and driftwood was found at 1.8 m a.r.1.

At the abandoned Indian village, on the right bank of the Mackenzie River, driftwood was found 1.5 m a.r.1. The village was built on 2 m - 2.5 m terrace, but no signs of recent floodings were found on the terrace in the vicinity of the village.

Between Fort Providence and Mills Lake high water marks were observed at 1 m a.r.1. and ice-shoved ridges on upstream shores of the islands at up to 9.5 m. At Mills Lake, the Mackenzie River widens to approximately 16 km and flood levels are less than 1 m a.r.1.

Below Mills Lake, the Mackenzie River narrows and the width varies from 4 km to 1.5 km. It is only 1 km wide in the vicinity of Cache Island and high water marks on this reach of the river were less than 2 m a.r.1.

On Cache Island (Site No. 6, Fig. 1) ice-shoved ridges were found at 7 m a.r.1. (Fig. 5). Ice injury to a tree was also found at 7 m a.r.1. Isolated boulders scattered above the highest limits (7 m) of ice-shoved ridges, but below the forested edge of the terrace, which forms the top of the island (Fig. 5), are probably remnants of ice-shoved ridges pushed to a higher elevation some time in the past. The height of ice-shoved ridges diminishes to 2 m a.r.1. midway along the island where it is the widest.



Fig. 5. Ice-shoved ridges on upstream side of Cache Island (Site No. 6 in Fig. 1).

X-ray photographs of increment cores taken from scarred trees and their description are given in Appendix 2 (Site No. 6, PSWH71-26-SE and -26-NW). An ice-injured white spruce was found on the bank of the island and increment cores were taken. The tree grows on the slope near the terrace edge, leaning 5° - 6° toward the river. One increment core was taken through the scar and one below the scar. As the oldest ring, dated 1867, is a few rings from the pith, the tree is at least 104 years old. In 1894 the tree began to form compression wood, which indicates that at that time the normal upright growth of the tree was disturbed. It is probable that floods undercut the roots of the tree, causing it to lean and the tree began to form compression wood to restore itself to an upright position. The last ring present in the increment core from the scar is from year 1934; but because it contains latewood, the injury could not have been inflicted during the spring floods in 1934.

In the increment core from below the scar, the tree ring formed in 1935 contains traumatic resin canals, near the earlywood and latewood boundary. Resin canals are believed to form when a tree is healing an injury. Because the 1934 ring contains latewood, and traumatic resin canals are found in the 1935 ring between earlywood and latewood, it appears that the injury occurred during the break-up in 1935.

Between Cache Island and Green Island near Fort Simpson the Mackenzie River flows in a channel 1 km to 1.5 km wide. High water marks have been observed at elevations less than 2 m a.r.1., for the greater part of the river, but on the 11.5 m to 12 m terrace, opposite Strong Point, driftwood was found on the slope of the terrace at 7.3 m a.r.1. Probably this high flood level resulted from the rising of the river level due to ice jamming near Fort Simpson.

High flood levels were also observed in the vicinity of Green Island. Increment cores of trees injured by river ice were taken at Site No. 7 (Fig. 1), which is located on the north bank of the Mackenzie River, opposite Green Island. Schematic profile (Fig. 6), shows the details of configuration of the bank, its vegetation and the location of a poplar injured by ice. The injured poplar grows on the slope near the edge of 14-18 m terrace. No signs of recent flooding were found on the terrace. The injury occurred at 11.5 m a.r.1., and this may indicate the highest level of flooding at the time of break-up.

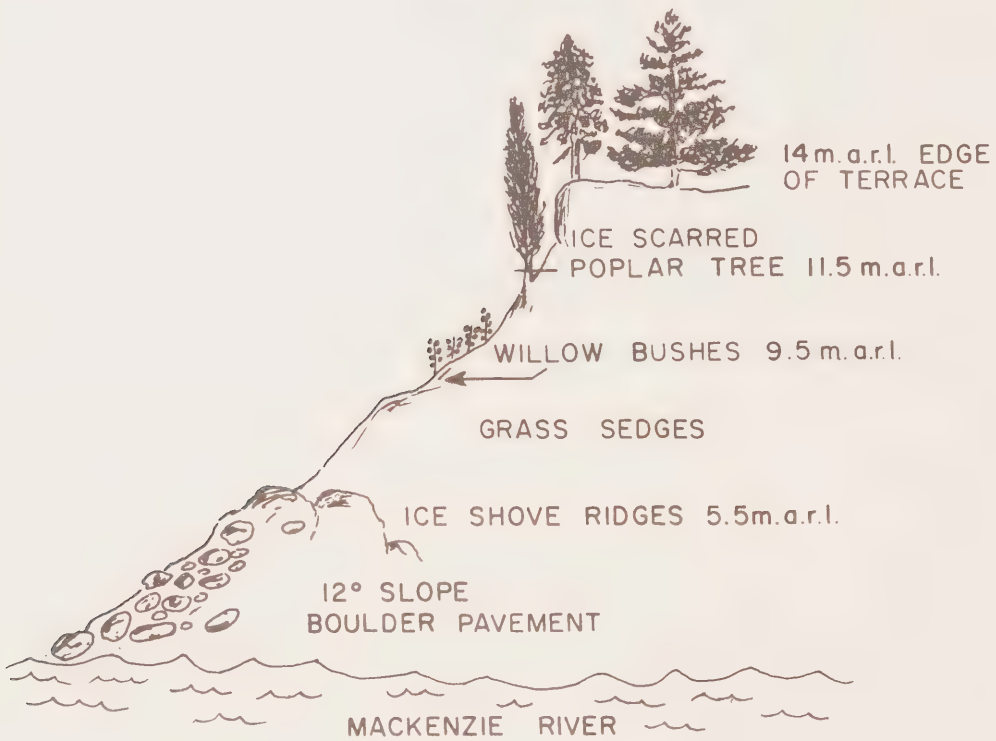


Fig. 6. Schematic profile of the Mackenzie River bank opposite Green Island (Site No. 7).

The date of the injury cannot be established with certainty, as tree rings are difficult to discern in some increment cores of poplars. Although the technique of measuring the density of X-ray photographs of increment cores (Parker 1972) has facilitated recognition of the rings, and experiments carried out in the Western Forest Products Laboratory, Vancouver, B.C. indicate that it is possible to distinguish the rings representing annual growth from others, the lack of a complete cross profile of the tree, limits analysis to an assumption that the injury occurred before 1950 (Appendix 2, Site No. 7). Also no signs of recent flooding were found on Martin Island.

THE LIARD RIVER MOUTH TO THE CONFLUENCE OF LIARD AND SOUTH NAHANNI RIVERS

From its confluence with the South Nahanni, the Liard River flows for a distance of about 90 km through a swampy plain in an incised valley; its channel varies in width from a few hundred meters to as much as 2 km. Farther downstream, the valley has the appearance of a canyon. The river flows over many rapids commencing below the mouth of the Poplar River and extending down the river for about 15 km. The highest rapids, known locally as Beaver Dam, are located about 57 km upstream from Fort Simpson just below the big bend of the Liard River. In July 1971 the drop from the crest was about 11.5 m high.

Break-up on the Liard River is crucial to navigation on the Mackenzie River. In the spring-time, the navigation is governed by break-up events at the confluence of the Liard and Mackenzie Rivers. The site is affected by catastrophic ice jamming and spring flooding.

Recorded dates of break-up (Table 2, Allen, et al., 1971) show that the main cause of ice jamming near Fort Simpson is the timing of break-up on the Mackenzie River. On the average, it takes place on May 26, that is 8 days later than on the Liard River (May 18). Break-up on the Liard River tends to occur earlier at Fort Liard (60° 14'; 123° 29') (May 4) than at Fort Simpson (May 18). Table 2 shows also that the Liard River is usually completely frozen over by November 13 at Fort Liard. But near the mouth of the Liard River at Fort Simpson this event occurs 10 days later, on November 23, on the average.

Driftwood has been found at the elevation of 11.6 m a.r.l. Fort Simpson residents report that in 1963 the ice jam reached the height of the road at the edge of the island and part of the population was evacuated as a precaution against flooding.

At Site 9 (left bank of the Liard River, 4 km from Fort Simpson) an injured poplar was found growing on the slope of an 18 m terrace. The scar was at 12 m a.r.l. Analysis of the X-ray photograph of the increment cores taken (Appendix 2, Site 9, core PSWH71-43W) indicated that the injury was inflicted in 1963. The data coincides with the date of maximum stage of river level recorded at Fort Liard on July 18, 1963. Driftwood was found at the same locality at 8.3 m a.r.l.

TABLE 2

Liard River and Mackenzie River - recorded dates of freeze-over and break-up at specific locations.

	Complete Freeze-Over	Water Clear of Ice
Fort Liard - N.W.T. Lat. 60° 14', Long. 123° 29', Liard River		
Early	Nov. 3	Apr. 27
Mean	Nov. 13	May 4
Latest	Nov. 26	May 16
Fort Simpson - N.W.T. Lat. 61° 45', Long. 121° 14', Liard River		
Early	Oct. 23	May 6
Mean	Nov. 23	May 18
Latest	Dec. 10	May 10
Fort Simpson - N.W.T. Lat. 61° 52', Long. 121° 16', Mackenzie River above Mouth of Liard River		
Early	Nov. 15	May 221
Mean	Nov. 27	May 26
Latest	Dec. 15	May 31

On the right bank, 8 km upstream from Fort Simpson, driftwood was found at 8.5 m a.r.l. Further upstream, 18 km from Fort Simpson, the highest level of recent river ice activity was found on the right bank: ice-shoved ridges reached 17.3 m a.r.l. (Fig. 7). Apparently the swift current divided by the largest island on the Liard River drives river ice onto the right bank of the Liard River to form ice-pushed ridges. Driftwood was found 27 km upstream on the left bank of the river at 9.6 m a.r.l. Further upstream, high watermarks were found at the same level as far as 45 km from Fort Simpson, on a small island, but on the upstream end of this island ice-shoved ridges reach 12.5 m a.r.l.

The reach of the river from this island to the sharp bend of the Beaver Dam is comparatively straight. On this reach of the river driftwood was found at 11 m a.r.l. and ice-shoved ridges at 8.5 m a.r.l. on the left bank.

A small island, 75 km upstream from Fort Simpson near the beginning of the rapids, is located close to the left bank of the river and cannot seriously hinder the flow. Driftwood was found at 2.5 m a.r.l. on the island, and at 2 m a.r.l. on the right bank of the river opposite the island.

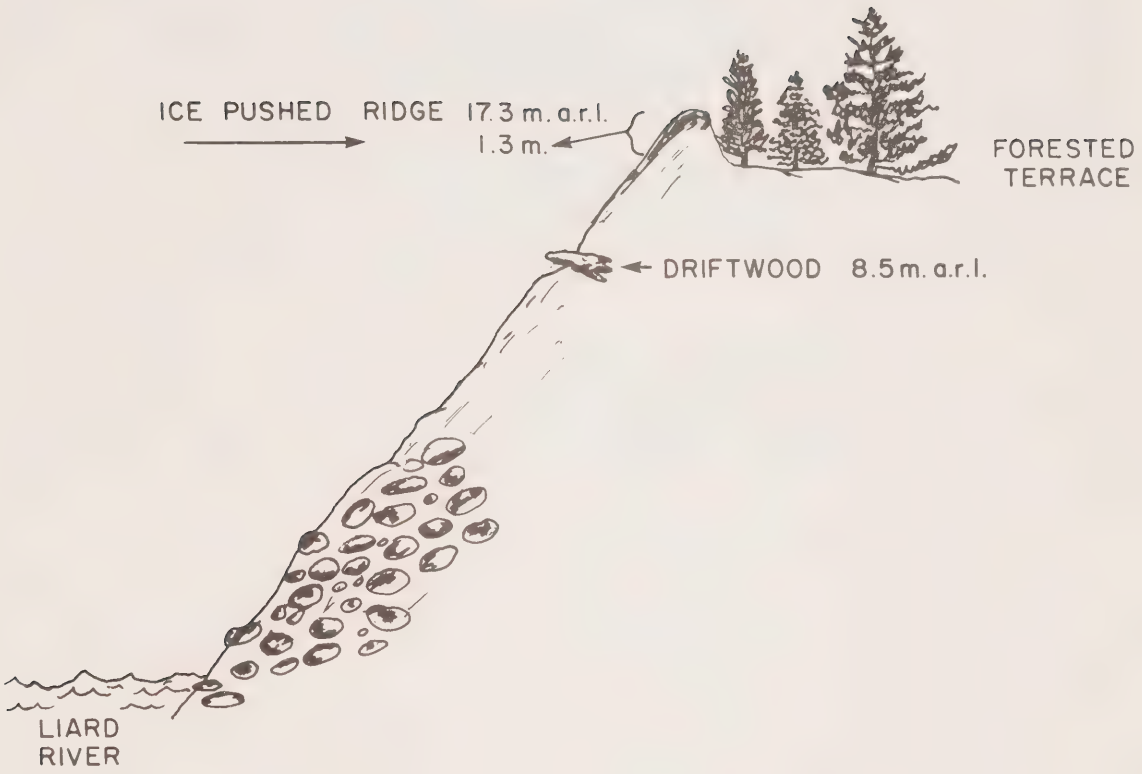


Fig. 7. Liard River, 18 km south from Fort Simpson - Schematic profile of the bank with ice-shoved ridges.

At Cape Island, 92 km upstream from Fort Simpson, the combined effect of the sharp river bend and the island obstructing flow is that the driftwood and ice-shoved ridges reach a height of 8 m a.r.l.

From just above Cape Island to the mouth of the Nahanni River, the Liard River widens considerably. Driftwood was found at up to 2 m a.r.l., except where the river flow is obstructed by river bends and islands where it was found at higher levels. On the left bank of the Liard River, 113 km from Fort Simpson (Fig. 2, Site No. 10), the flood water, divided by the small island in the middle of the current, deposited driftwood at up to 5 m a.r.l.

The flow of the Liard is constricted by several islands 145 km from Fort Simpson. On one of these islands (Fig. 2, Site No. 14) over-bank silt deposits are found at 7 m a.r.l.

THE MOUTH OF SOUTH NAHANNI RIVER TO THE FIRST CANYON OF THIS RIVER

Navigation upstream from the settlement of Nahanni Butte to Hot Springs at the entrance to the First Canyon, is difficult because of the swift current, braided channels with many shoals, floating driftwood, and dead heads.

Flood levels at Nahanni Butte, at the mouth of the South Nahanni River, deserve special attention. The level of spring flooding near the settlement, according to local inhabitants, is 5 m a.r.l.; but the level was exceeded during a summer flood in July 1963 when the flood reached some of the houses at the level of 7 m a.r.l.

The South Nahanni River flows between the Yohin Ridge and the Nahanni Range in many braided channels called locally "the splits". In this reach the river channels are contained by 2 m terraces on which driftwood and silt deposits were found, indicating that they were subject to flooding (Fig. 2, Site No. 12).

A boat ascending the South Nahanni River from Yohin Ridge to First Canyon encounters less braiding and narrower channels than below Yohin Ridge. At the entrance to the First Canyon (Fig. 2, Site No. 11) there is a 5 m terrace where on the side of the terrace driftwood and flood silts were found at 4 m a.r.l.

In the vicinity of the Hot Springs (Fig. 2, Site No. 11) a leaning tree with the top of its trunk broken off and with a branch which took over the upgrowth was found on the 5 m terrace. This tree grew at the edge of a terrace which was evidently undercut by flooding, causing it to lean. (Fig. 8).

The analysis of X-ray photographs of the cores (Appendix 2, Site No. 11) PSWH71-67A, -67B, -67C and -67D, indicates that the flooding happened in 1877 when the tree was at least 10 years old. The date is indicated by compression rings which started to form in 1877 and continued to form until 1892 in an attempt to regain an upright position.

SUMMARY AND CONCLUSIONS

The data on the position and maximum height of marks left by floods and river-ice action were collected during a canoe trip in summer 1971. The route followed along the Mackenzie River from Fort Providence to Fort Simpson, thence up the Liard River to the confluence of the Liard and South Nahanni Rivers and up the South Nahanni to the First Canyon, returning along the same rivers to Fort Simpson.

Maximum height of flood level as indicated by driftwood and silt deposits varies in different reaches of the Mackenzie River. But as the Mackenzie River flows out of Great Slave Lake, these variations are small, that is less than 1 m for most of its course to the Liard River. Flood levels, however, become greater in the last reach of this course. On the left bank opposite Strong Point, driftwood was observed at 7.3 m. Such high flood levels are caused by ice jams which occur at the confluence of the Mackenzie and Liard Rivers at the time of break-up. Here on Fort Simpson Island flood deposits were found at 11.6 m a.r.l.

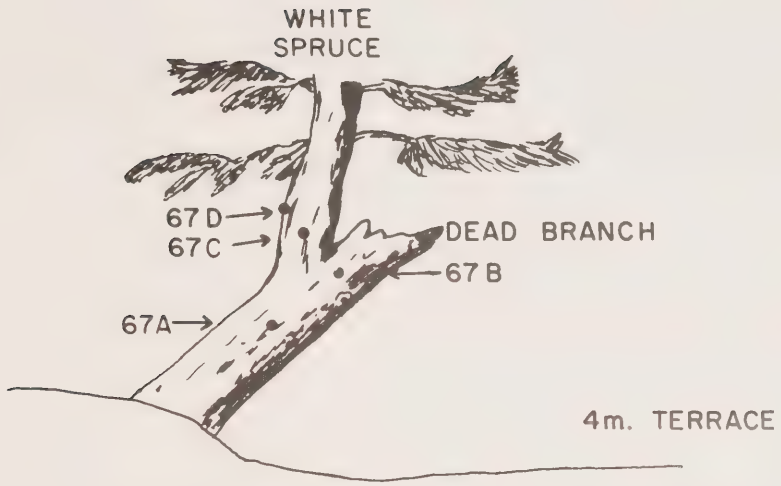


Fig. 8. Leaning tree on the Liard River near Hot Springs.

The height of marks left by river ice exceeds, in many locations, the height of marks left by flood waters. Ice-pushed ridges and ice injury to trees were found on the upstream side of the islands at 7 m and even at 9.5 m a.r.1., whereas on the side of the islands the highest flood marks were 2 m a.r.1. Ice injuries to the trees found near Green Island (Fort Simpson) at 11.5 m a.r.1. indicate that ice-jams have formed between Green Island and the north bank of the Mackenzie River.

It is emphasized that, above the confluence of the Liard and Mackenzie Rivers, except for the shores, no signs of flooding were found on Martin Island and Green Island (near Fort Simpson).

On Fort Simpson Island, however, below the confluence of the Liard and Mackenzie Rivers, many indications of flooding over a considerable part of the island were observed. The rising river inundated extensive areas of the town of Fort Simpson so that a part of the town had to be evacuated during the floods at break-up in 1963 and 1972.

Influenced by the mountainous part of the drainage basin and lack of flow control by a lake the Liard River has extremely variable discharge and stage. The maximum height of flood levels on the Liard River, as indicated by driftwood, varies from approximately 2 m to 7 m a.r.1. between its confluence with the South Nahanni River and Cape Island; 12.5 m a.r.1. below the Beaver Dam Rapids and 12 m a.r.1. near its mouth. In some reaches of the river the current during flood conditions has driven the ice onto the shore to a height of 17.3 m, e.g., on the right bank of the Liard River, located at 12.9 km from its mouth.

Maximum height of flood levels on the South Nahanni River has been observed at 4 m a.r.l. near Hot Springs. Southeast of Yohin Range where the South Nahanni River flows in braided channels the highest flood marks were found at 2 m a.r.l. They attain the maximum height of 7 m a.r.l. at Nahanni Butte where the river flows in one channel.

The height of floods occurring at the time of break-up on the South Nahanni can be exceeded by sudden floods during the summer due to the orographically induced precipitation.

Dendroclimatic analysis has shown that maximum tree-ring density data of a stand of white spruce on the Liard River has a positive correlation with the mean maximum August temperature at Fort Simpson for the years 1928-1970.

Examination of increment cores has indicated the dates of floods which could not be obtained from other sources.

In conclusion, the following recommendations are presented:

1) No pipeline crossing should be made below the rapids in the last 60 km of the course of the Liard River, because of the great variability of Liard River stage and discharge and because this part of its course is subject to frequent catastrophic flooding and ice-jamming.

2) A pipeline route, especially any proposed for the transport of oil, should be directed to the east side of the Mackenzie River. The crossing of the Mackenzie River should be located above its confluence with the Liard River at a safe distance from the influence of ice-jams which recur there annually.

ACKNOWLEDGEMENTS

I would like to thank Ernie Hamm for his able assistance in the field work, Don MacKay for his continued interest and advice in my research, Marion Parker, University of British Columbia and the staff of the Western Wood Product Laboratory, Vancouver, B.C., for processing and interpretation of increment cores and Martha Skulski for critical reading of this report.

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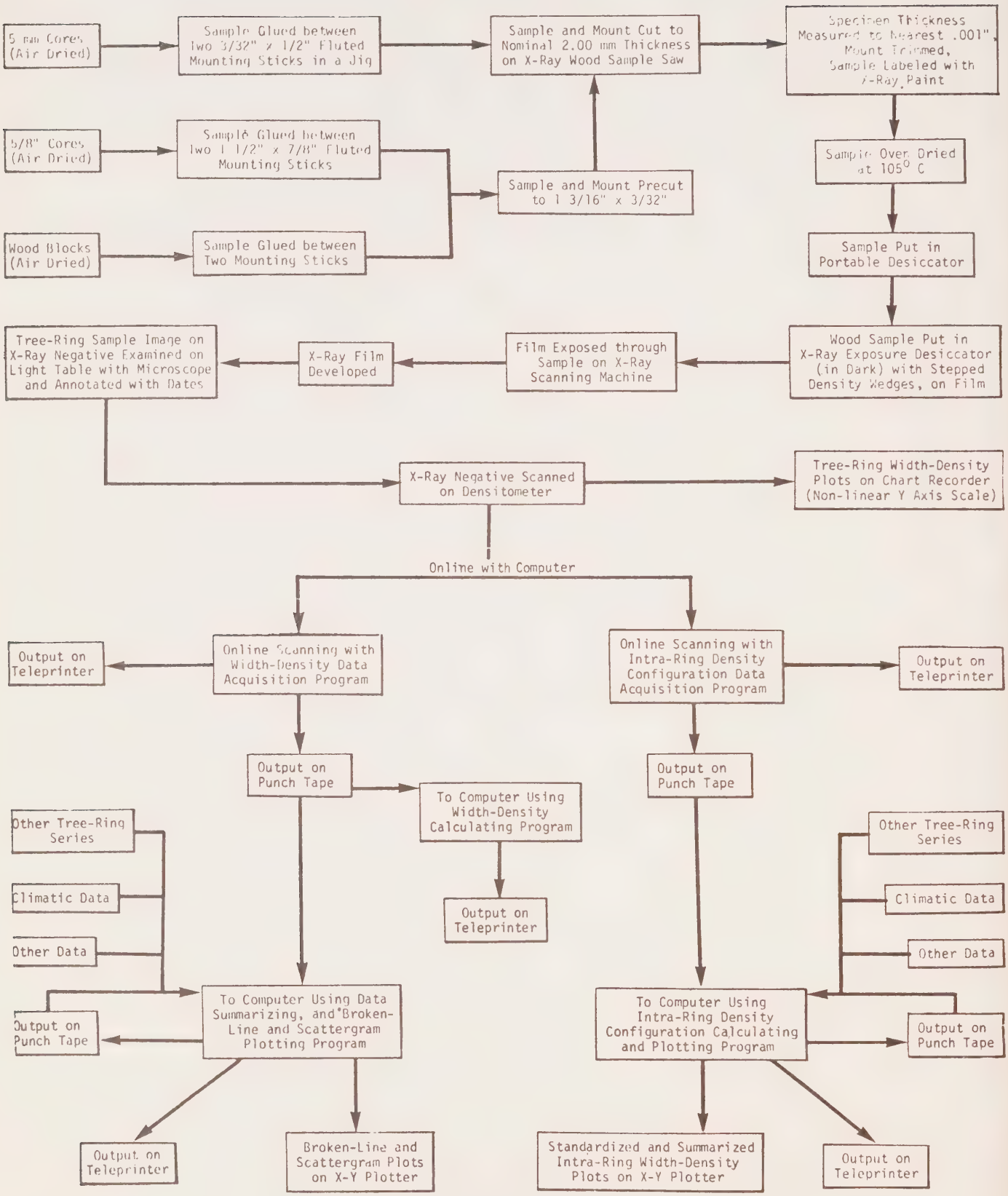
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APPENDIX I

ROUTINE PROCEDURE USED TO PRODUCE

DENDROCHRONOLOGICAL DATA BY X-RAY DENSITOMETRY

(AFTER M.L. PARKER, 1972)



APPENDIX 2

EXAMINATION OF SCARRED-TREE CORES FROM X-RAY NEGATIVES AND MOUNTED CORES

(After M.L. Parker)

Site No. 2 MACKENZIE RIVER ISLAND, 3 km west of Fort Providence
Coordinates: 61°21'42"
117°41'58"

White Spruce

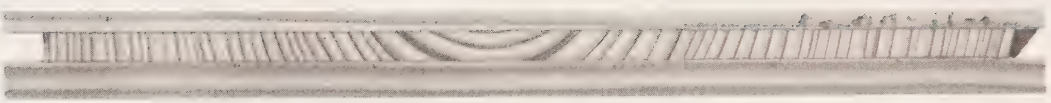
Height of injury: 9 m above main river level (a.r.l.).
Ice shoved ridges at 9.5 m.



Sample PSWH71-1E

Dates - Outside, on both ends (bark on one side), 1971.
Innermost ring, near pith, 1935.

Site No. 2



Sample PSWH71-1 Through scar, cross-dates with PSWH71-1E using ring widths.

Dates:- One side: bark present, outside date 1971, near pith, 1935. Other side: through scar, 1969 vary variable. Only early wood is present in the 1969 ring and the variable surface indicates that some of that ring is missing because of erosion of the surface of the tree trunk where the core was taken. The presence of early wood indicates that the injury could not have been inflicted by ice flows at 1969 break-up, but the injury inflicted at the time of 1970 break-up could have removed the 1969 latewood and the 1970 growing season would not have been initiated at the time of break-up.

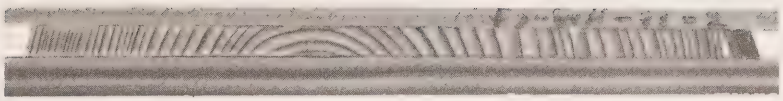
Site No. 2



Sample PSWH71-2E Below scar.

Dates - Both sides of core date 1971; one side has bark. Oldest ring (few rings from pith) dates 1939.

Site No. 2



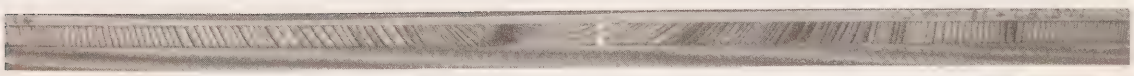
Sample PSWH71-2 Through scar.

Dates - One side, with bark, 1971.
Inside, near pith, 1932.
Side through scar; last ring, 1969; latewood present.
Injury probably occurred between the 1969 and 1970 growing seasons.

Site No. 5 CACHE ISLAND
Coordinates: 61°22'30"
120°05'00"

White Spruce

Leaning towards the river at the height of 8 m on the downstream bank of the island. The tree was disturbed by mass movement of the slope.



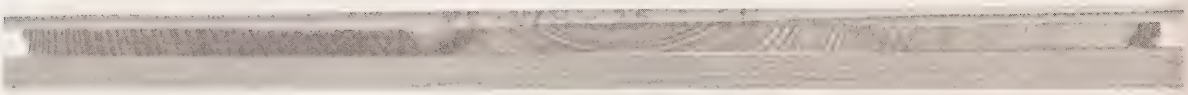
Sample PSWH71-25-SW

Dates - The increment core shows compression wood. For dating the event which disturbed the normal growth of the tree, a section of the tree is necessary rather than an increment core.

Site No. 6 MACKENZIE RIVER, CACHE ISLAND
Coordinates: 61°22'30"
120°05'20"

White Spruce

Height of injury: 7 m a.r.l.



Sample PSWH71-26-SE

Dates - Bark, 1971. Innermost ring (few rings from pith) 1867. Last ring present, 1934; latewood present; injury occurred after the 1934 growing season. The outside of the core is broken and some rings may or may not be missing. Cross-section would have given better records. Compression wood starts on this side of the core at 1894.

Site No. 6



Sample PSWH71-26-NW Through scar.

Dates - Bark, 1971; good cross-dating with other core inside ring, 1868. Traumatic resin canals occur in the earlywood of the 1935 ring, near the earlywood-latewood boundary.

Site No. 7 MACKENZIE RIVER TERRACE, north of Green Island
Coordinates: 61°50'05"
120°57'30"

Poplar

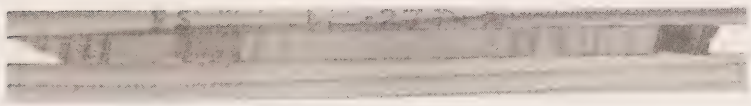
Height of injury: 11.5 m a.r.l.



Sample PSWH71-27-N1

Dates - Outside bark, 1971; inside ring (not pith), 1921.
Dates tentative.

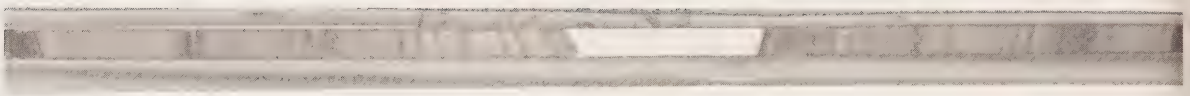
Site No. 7



Sample PSWH71-27-N2

Dates - Outside bark, 1971; inside ring (not pith), 1921.

Site No. 7



Sample PSWH27-N3

Dates - Outside bark (on both sides), 1971; centre missing (rot). Innermost ring, right side of the core, in 1930's; innermost ring, left side of the core, 1918. Good cross-dating between N1, N2 and N3.

Site No. 7



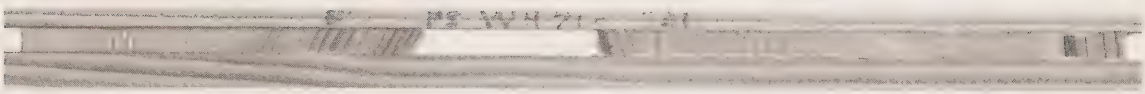
Sample PSWH71-27 Through scar.

Dates - Outside bark, 1971. Core taken through portion of tree that has grown over scar and into the wood which grew before the injury. The injury occurred before 1950, but the exact date of the injury cannot be determined from this core because not enough rings of the specimen that grew before the injury are available for cross-dating. The injury could have been dated if a complete cross-section were available.

Site No. 9 NEAR THE MOUTH OF LIARD RIVER
Coordinates: 61°50'05"
121°19'05"

Balsam Poplar

Height of injury: 12 m a.r.l.



Sample PSWH71-41 Above scar.

Dates - Tentative.
One side: bark, 1971; inside, 1910.
Other side: no bark, 1971.
Centre is missing (rot).
Preliminary examination of cross-dating gave encouraging results, but more work with this species has to be done before dates can be established.

Site No. 9



Sample PSWH71-41 Through scar.

Dates - The last ring present on this core appears to be from 1962; inside ring (not pith), 1908. Cross-dating with other core is good.

Site No. 9



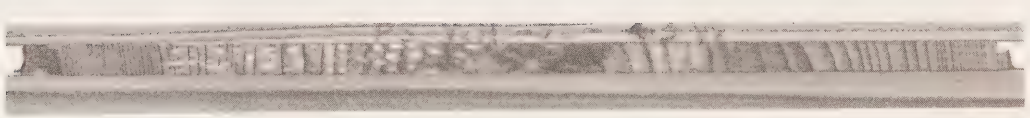
Sample PSWH71-42-NW Good record of injury.

Dates - There is "normal" growth until 1962; than compression wood starts with the ring in 1963. This suggests that the tree was pushed to one side, into leaning position between 1962 and 1963 growing season. Good cross-dating with PSWH71-43-W.

Sample PSWH71-42-SE

Dates - Last ring present, 1962; latewood present. Good cross-dating with other side of core and with sample PSWH71-43.
The ring has a uniform boundary, indicating that none of the injured portion was lost in collecting; but it would still be better to have a complete cross-section of the tree through the scar. Injury occurred probably between 1962 and 1963 growing seasons.

Site No. 9



Sample PSWH71-43-W

Dates - One side of core: bark, 1971; pith, 1919.
Other side of core, through scar: last ring present 1962, (latewood present).
Injury occurred after the 1962 growing season. Note that 1962 ring is the last ring present on the injured cores from samples -41, -42 and -43.

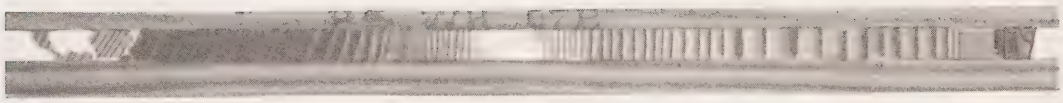
Site No. 11 HOT SPRINGS, SOUTH NAHANNI
Coordinates: 61°15'00"
124°02'50"

Sample PSWH71-67A

Dates - No bark present.
Outside, 1971.
Inside, 1867 (some distance from pith).
"Normal" rings are visible until 1876; compression wood from 1877 until about 1892. Poor quality of core makes it difficult to count rings between 1860 and 1870.



Site No. 11



Sample PSWH71-67B

Dates - Outside bark, 1971; cross-dates with other cores. Very small rings starting with 1957 ring. Gap (rot) before 1921 (52 rings before this gap). Probable date of the innermost ring (some distance from pith) in 1863. Tentative cross-dating with sample PSWH71-67A; the same pattern of compression wood starting at 1877; the gap makes dating tentative.



Site No. 11

Sample PSWH71-67C

Dates - Outside, 1971.
Inside, 1904 (not pith).
Fairly even growth through series.

Site No. 11

Sample PSWH71-67D

Dates - Outside bark, 1971.
Innermost ring, 1903, (near pith).
Fairly even growth through series.

DOCUMENTATION OF AN EXTREME SUMMER STORM IN THE MACKENZIE MOUNTAINS, N.W.T.

by

D. K. MacKay, S. Fogarasi and M. Spitzer

Technical Report 6 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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ABSTRACT

Documentation of a severe rainstorm in the Mackenzie Mountains during July 1970 is presented on the basis of limited data. The basic atmospheric processes giving rise to the excessive precipitation, the runoff response in certain west-bank tributaries of the Mackenzie River and the storm-caused changes in river flood plains are examined and discussed. Tree-ring data suggest that a storm of similar intensity and magnitude has less than 1% chance of happening in any given year. Lesser storms, however, are common and these have important implications for gas or oil pipeline construction and maintenance, tourism and other activities of man.

DOCUMENTATION OF AN EXTREME SUMMER STORM IN THE MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES

by

D.K. MacKay, S. Fogarasi and M. Spitzer

Introduction

An intense rainstorm over the Mackenzie Mountains, Northwest Territories, on 19th - 21st July 1970, caused flooding and major changes to channel islands, banks and bedforms in rivers draining the area. The rivers most severely affected were the Redstone, Keele, Mountain and Arctic Red (Fig. 1), all west-side tributaries of the lower Mackenzie River. Other rivers such as the South Nahanni, Pelly, Stewart and Peel increased in flow but did not reach flood stage.

The probable area of storm rainfall could have ranged up to 80,000 km^2 (30,000 sq mi). The storm boundaries (Fig. 1), however, are somewhat vague and indeterminate as no weather stations exist in the Mackenzie Mountains. The boundaries illustrated are derived from meteorological data collected some distance from the storm centre, from weather maps and satellite photographs, as well as from hydrometric observations and visible geomorphic and vegetative effects in the area.

The 1970 storm was unusual because of its apparent intensity and because of the damage wrought to some sections of the river flood plains. In some reaches, small channel islands were entirely eroded and whole stands of trees were bent or uprooted and flattened by the force of the flood wave. In some parts of the flood plain and surrounding areas, the vegetation mat was torn rug-like from its soil underpinnings and pushed aside by the moving water.

In the Mackenzie Mountains, summer storms are relatively common events. In any summer season, a number of these may generate sudden and significant rises in river stage. Henoch (1960) mentions the prevalence of such storms in the upper reaches of the Arctic Red River. He suggests that the storms are orographic and convectional in origin and that rivers may respond by rising as much as 6 m (ca 20 ft) or more in a few hours.

The importance of keeping a record of extreme storm events in the north and the damage they cause has recently been emphasized by proposals for gas and oil pipeline development in the Mackenzie River valley. One possible route for a gas and/or oil line from Prudhoe Bay, Alaska and the Mackenzie Delta to southern Canada lies along the west side of the Mackenzie River. Many of the mountain tributaries which would have to be crossed are subject to flash flooding, extensive and rapid flood plain erosion, scour, fill and reworking of bedforms. Activities such as seismic or pipeline surveys, construction, prospecting and tourism could involve unrecognized risks, especially on the flood plains of the mountain tributaries. The documentation of the 1970 event was undertaken to provide some insight into the origin and possible effects of such storms in the Mackenzie Mountain area.

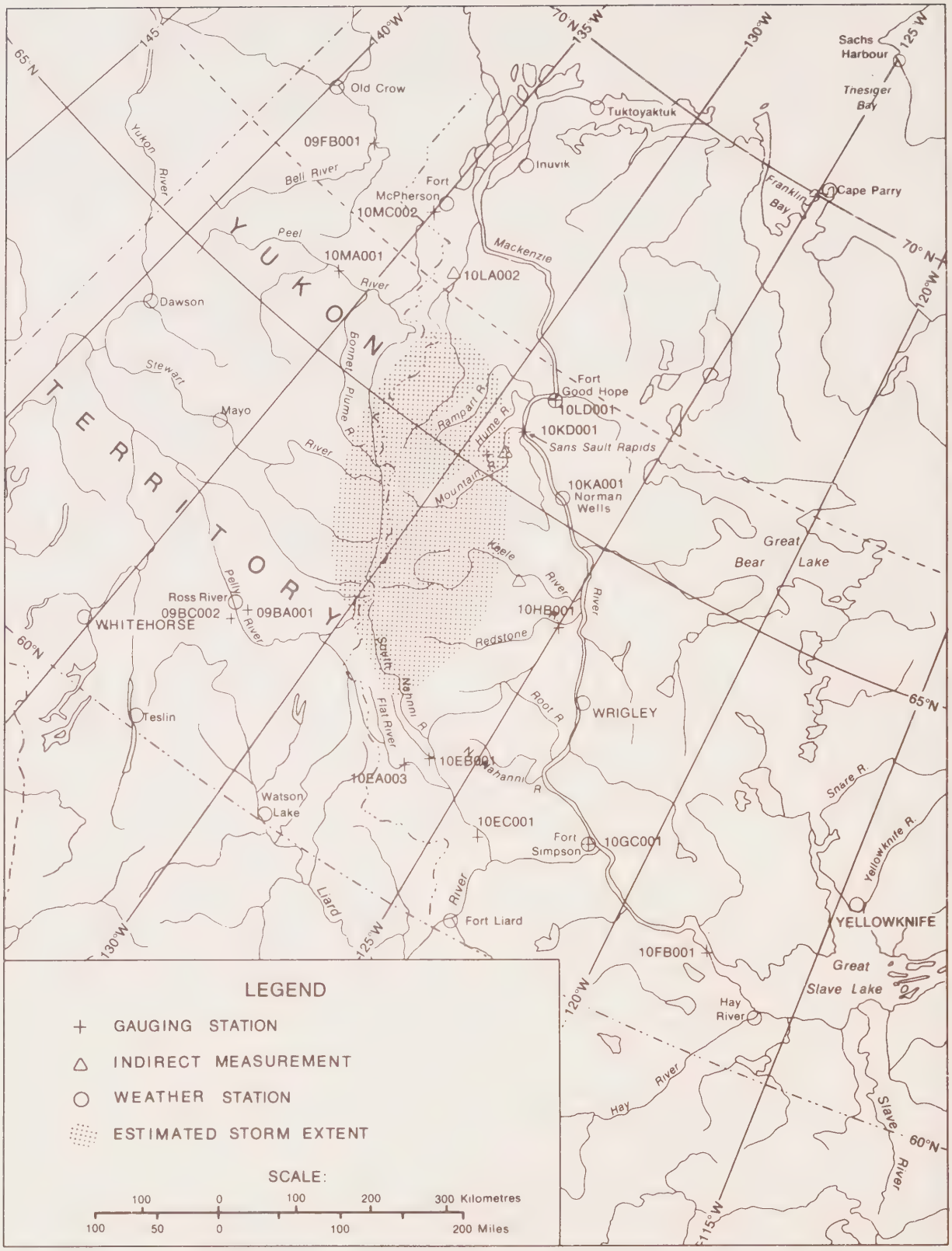


Figure 1. General location map showing weather stations, gauging stations, indirect measurement sites and possible extent of rainstorm, 19-21 July, 1970.

Atmospheric Processes

Little indication of the severe character of the July 1970 storm is contained in weather reports from meteorological stations near the Mackenzie Mountains. Generally, stations along the Mackenzie River reported moderate amounts of precipitation associated with thunder and lightning.

A purely meteorological analysis of the storm has been presented elsewhere (Fogarasi, 1971). Here, the examination of weather data from Norman Wells, the station closest to the storm centre, is being undertaken to document the convective potential of the atmosphere and the synoptic scale processes that were dominant during the event.

The first phase in the analysis was aimed at the detection of the air mass variation and inherent instability at Norman Wells by means of the scatter of the potential temperature values (θ) within the thetagram band plotted in Figure 2. The band represents the θ values of the radio ascents for the period 0000 GMT (1700 MST) 15 - 21 July. On this basis, there was no substantial change in the overall characteristics of the air masses during the week examined. The lower straight section of the band suggests thorough mixing with neutral lapse rate between the surface and 700-mbar level; the break from the 700-mbar level up indicates uniform warming divorced from surface effect. Reinelt (1970)also recognized that air masses which were thoroughly mixed in the lower layers on the leeside of the Rockies frequently yielded strong instability under the influence of the mountain barrier effect. The instability of the air-mass structure is revealed in Figure 3 which shows an isentropic time-cross section for Norman Wells. The lowering of the 300°K isentrope to 0000 GMT on 19 July indicates a warming period. The rise of the same isentrope between 19 - 22 July is evidence of gradual (possibly advective) cooling aloft and a consequent rapid increase in instability. In addition, the 5-day span of the time-wave formed by the 310°K isentrope over the period 16 - 21 July manifests the passing of a wave of synoptic scale.

The increase in instability can be further demonstrated by use of the Sly convective index (Sly, 1964). Since instability is usually accompanied by airflow convergence at low levels and/or a large-scale vertical velocity field aloft, the Sly index (Fig. 4) shows an increase with the deepening of the low and where the calculated large-scale vertical velocity at 600-mbar level is at maximum, -4.5×10^{-3} mbar s^{-1}, and the velocity convergence at 900-mbar level is -3.4×10^{-5} s^{-1}. Figure 4 also indicates that the Sly index maximum is closely related to a large-scale surface low-pressure system.

Figure 5 shows a time cross-section of temperature and wind speed for Norman Wells, close to the centre of low. Near the surface, the temperature pattern could be considered a qualitative measure of the diurnal mixing. Temperature along the 750 and 700-mbar pressure heights still shows slight waving patterns which, in comparison with the low-level temperature curves, indicate a shift of phase to the right; that is, vertical mixing with time lag aloft. The assumption of lower mixing, based on Figure 5, is in agreement with the mixing evident from the nertral profile of the thetagrams of Figure 2.

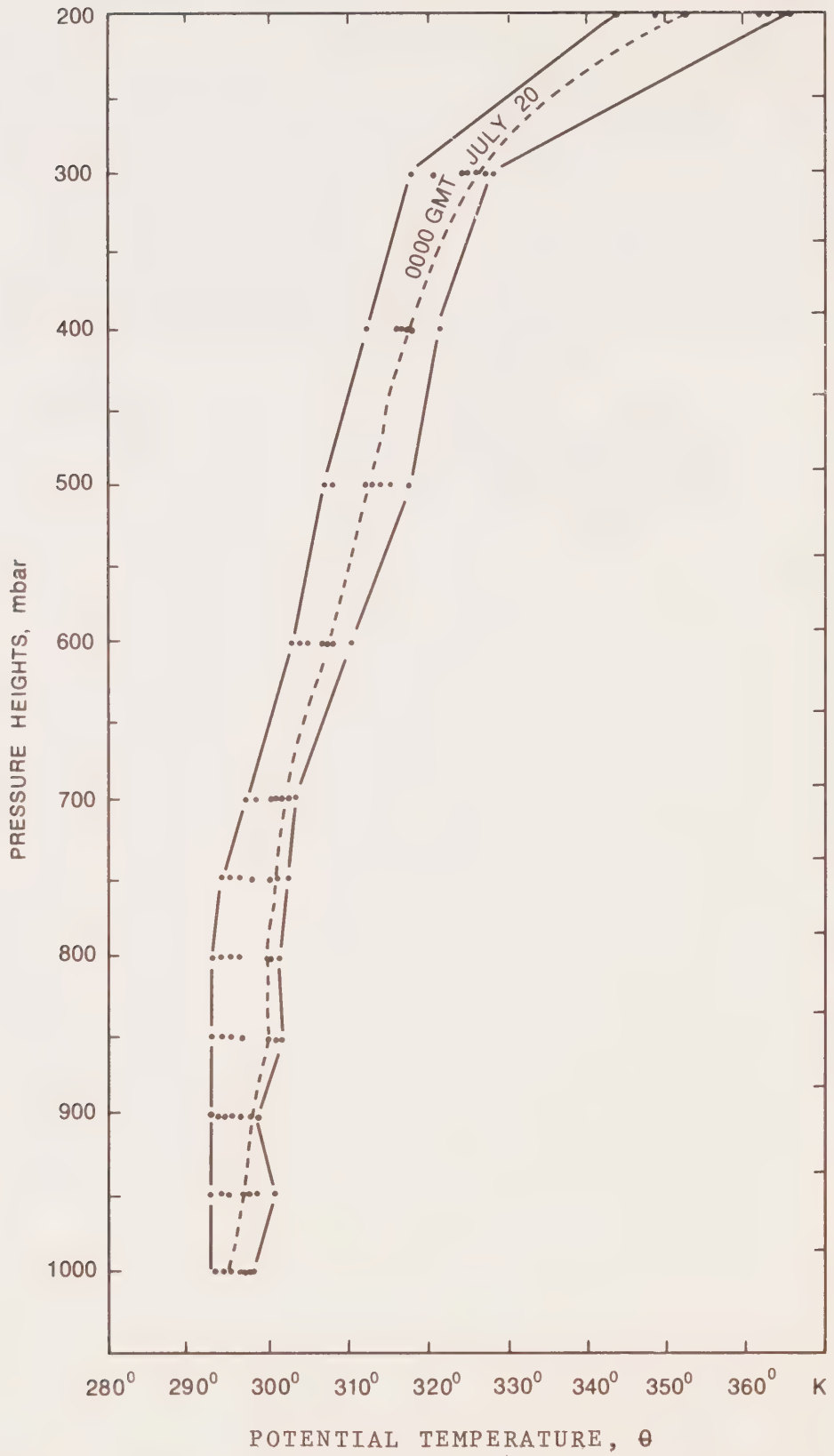


Figure 2. Scatter band of the potential temperature values (O) at Norman Wells during 15-21 July at 0000 GMT. (1700 MST), 1970.

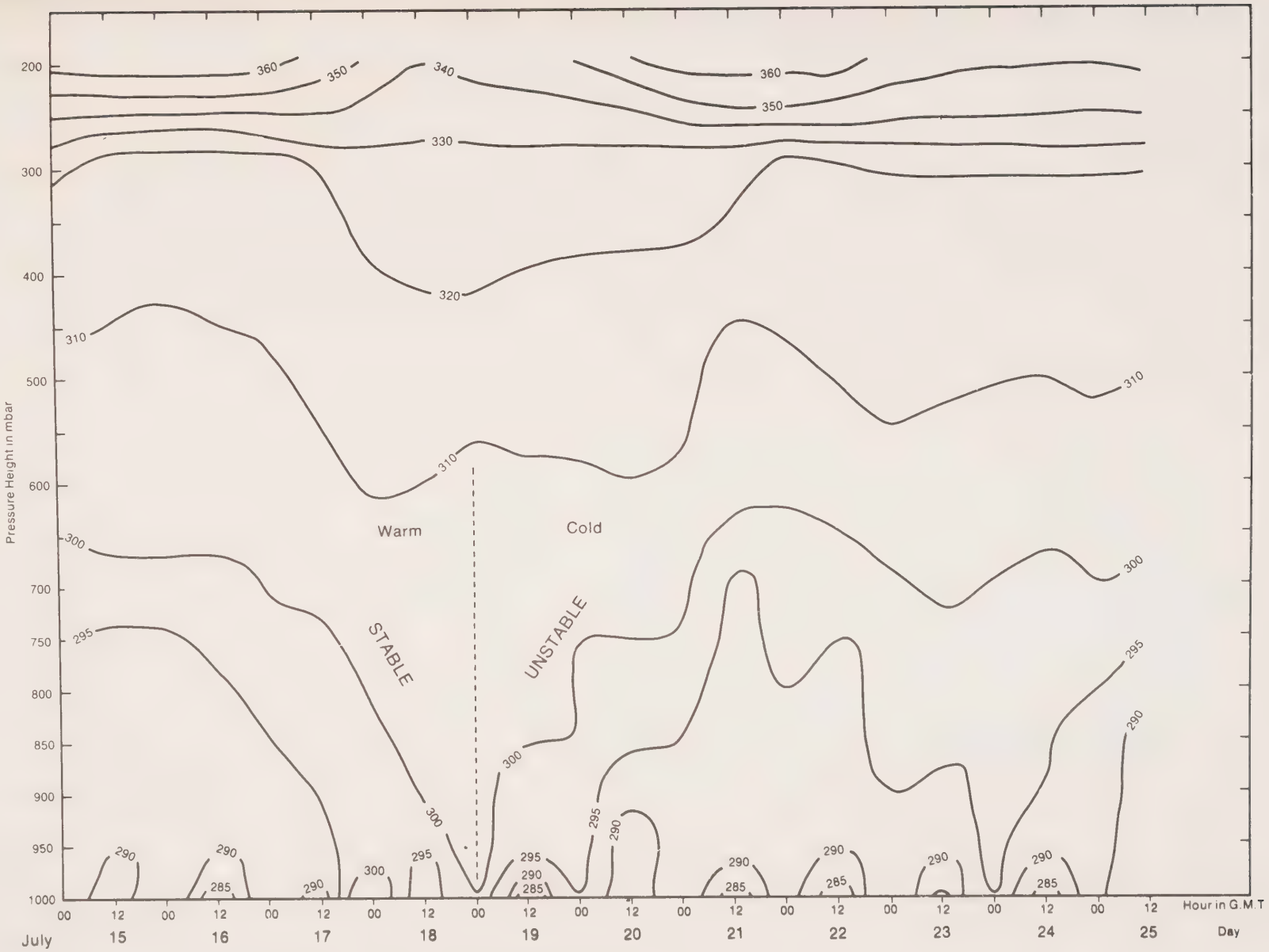


Figure 3. Isentropic time cross-section, Norman Wells, N.W.T., 15-25 July, 1970.

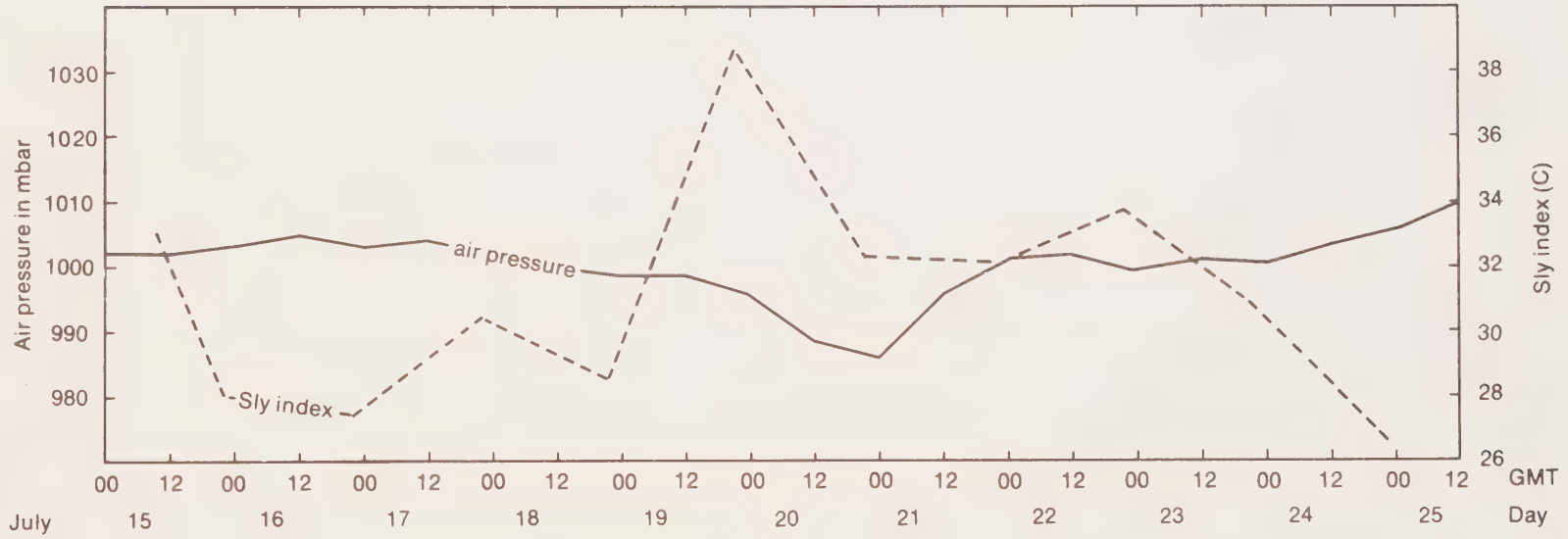


Figure 4. Variation of surface air pressure and Sly index at Norman Wells, 15-25 July, 1970.

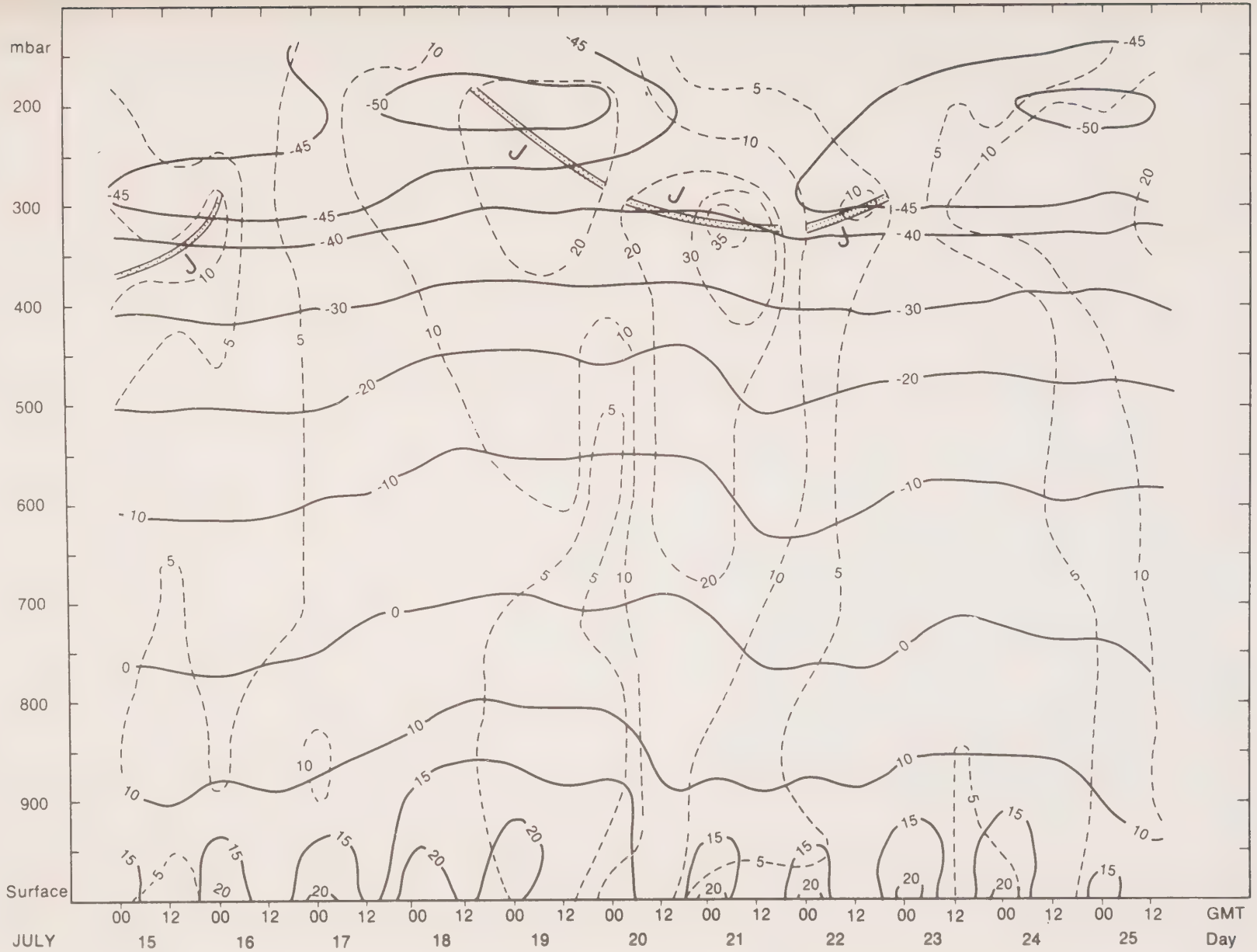


Figure 5. Time cross-section of air temperature in C° (solid lines) and isotachs in m sec 1 (dashed lines). Time variation of the jet streams is indicated with letter "J" (double lines).

In Figure 5 the momentum transfer from above is displayed by the 10 m s^{-1} downhanging isotach pattern. Between 19 - 21 July the rise of the 295°K and 300°K isentropes (Fig. 3) and the Sly index (Fig. 4) indicated strong instability and at this time the cross-section of the precipitable moisture reached a maximum (Fig. 6).

A further assessment of the possible influence of convection on local precipitation was made based on the 0000 GMT 20 July radiosonde ascent for Norman Wells (Fig. 7). The ascent curve indicates that a possible 5°C overheating at 1000-mbar level cannot produce cloud because the warm rising air along the dry adiabat lowers its temperature to that of the ambient air at 850-mbar height. This elevation is beneath the condensation level which is indicated by the 7.1 g/kg condensation isogram. The northeasterly winds at 850-mbar height flowing over the Mackenzie Mountains mix with the rising pockets of air from the surface. The northeasterly flow then introduces additional heat from the mountain tops into the mixture of air. This air rises to the level of the mean condensation isogram at 690-mbar where cloud ceiling may form and the cloud top may reach up to 390-mbar level along the wet adiabat. On the basis of Figure 7 a high level heat input and the triggering of precipitation by the Mackenzie Mountains seems to be active. In summary, the analysis of the Norman Wells data suggests that the presence of an organized low-pressure system steered by synoptic waves superimposed on thermal convection was responsible for the large amount of precipitation.

Runoff Response

The northern gauging-station network which includes the Mackenzie Mountains region is very sparse; in fact, only one river severely affected by the storm, the Arctic Red, has a gauging station located on it. Unfortunately, the storm record for the Arctic Red River was lost when the gauge shelter was flooded to a depth of 2.1 m (7 feet) which, in turn, caused the recording equipment to malfunction. The Redstone, a less severely affected gauged river, still reached a peak of sufficient dimension to wash out the orifice which also resulted in a loss of record.

Data from five gauging stations operating on the Mackenzie River were used as an aid in assessing storm runoff. An additional eight gauging stations whose drainage areas were located within the zonal fringe of the storm were examined to locate roughly the storm's center, extent and effects. Table 1 lists all gauging stations and their corresponding station codes (Fig. 1) used in this study.

It is evident from the gauging station records that the storm was centered on the eastern slopes of the Mackenzie Mountains range in the headwaters region of the Arctic Red and Mountain rivers. The runoff in the Keele River basin was affected to a lesser extent while that of the South Nahanni, Ross, Pelly and Peel River basins was only slightly affected by the storm. In fact, higher peaks had been recorded in 1970 prior to the storm event in the South Nahanni, Ross, Pelly and Peel Rivers.

The hydrographs for the gauging stations on the Porcupine River below Bell River and on the Peel River above Canyon Creek continued to recede at a constant rate throughout the storm period showing that these basins

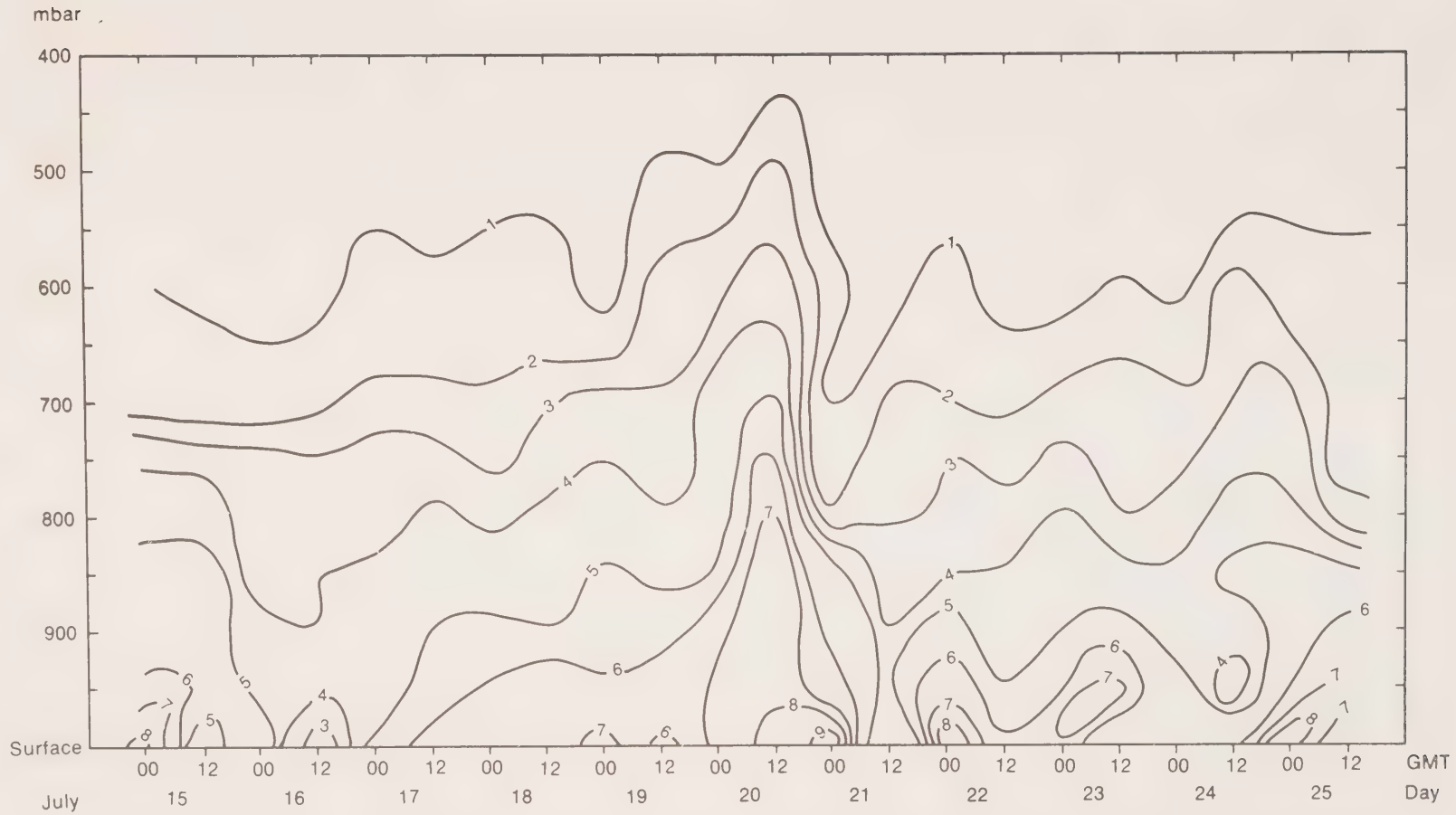


Figure 6. Time cross-section of precipitable moisture in grams of moisture per kilogram of dry air.

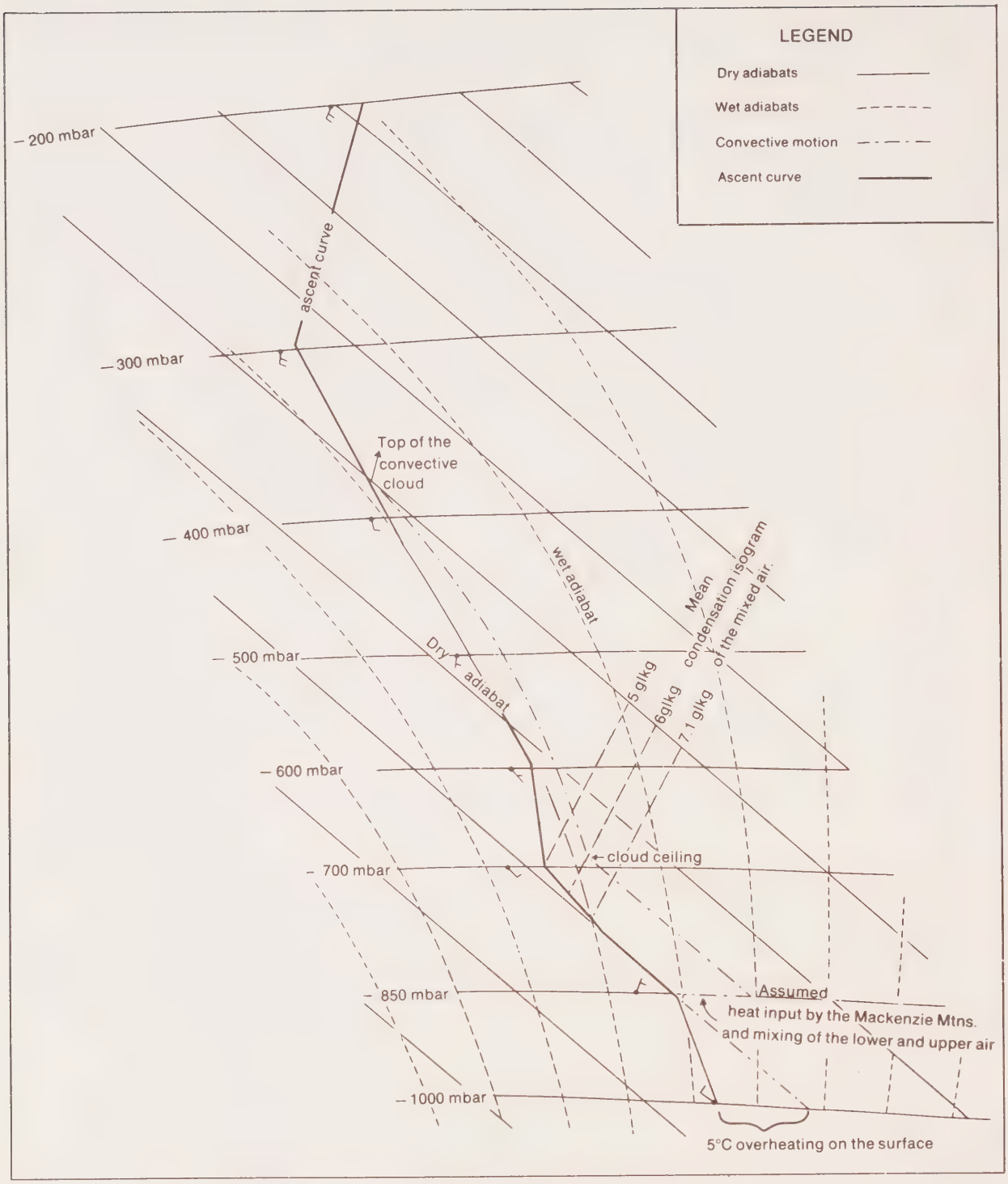


Figure 7. Tephigram illustrating ambient temperature distribution and lifting condensation level over Norman Wells at 0000 GMT 20 July, 1970.

were located completely outside the storm boundaries. Since the Peel and Porcupine Rivers rise in the Ogilvie Mountains it is apparent that this range was not within the storm area. The station located on the Peel River above Fort McPherson, however, recorded a small peak discharge which indicates that the basin of the Snake River, a lower tributary of the Peel, was within the fringe area of the storm limits.

A total of three indirect measurements (slope-area surveys) were made to determine instantaneous peak discharges. Surveys were conducted on the Arctic Red River at the gauging station site, on the Mountain River below its junction with the Gayna River and on the Keele River below its junction with the Nanlin River. In addition, an attempt was made to do a survey on the Redstone River, but high-water marks were not sufficiently defined to outline the water surface profile during the peak flow, nor could an instantaneous high water level be defined from the gauging-station record.

All the available information on peak discharge for streams affected by the storm is listed in Table 2. The instantaneous peak unit runoff for the storm-affected region is shown by isorunoff lines in Figure 8. These lines are estimates made on the basis of little data and serve only to give an impression of the variation and intensity of runoff throughout the storm area. Such isolines should not be used for quantitative determination of instantaneous unit runoffs at ungauged locations. Peak flow at ungauged locations can be estimated by the Creager envelope curve method (Creager et al., 1961) according to the equation:

$$q = 46\ CA^{(0.894A^{-0.048} - 1)}$$

where q = unit runoff in cfs/sq mile

C = envelope curve coefficient

A = drainage area in square miles

The envelope curves for Creager's equation with the coefficient C equal to 30, 60 and 100 are depicted in Figure 9 in both English and metric units. Included on this figure are plotted points for the instantaneous peak discharges for the Arctic Red, Mountain and Keele Rivers. Using this method, peak flow magnitudes may be determined for ungauged streams or for points on gauged streams other than at the gauging-station location as long as the meteorological conditions and characteristics of the basin are similar. For example, using this curve for a site on the Arctic Red River with a total drainage area of 2590 km^2 (1,000 square miles) the unit-peak discharge for the flood event has been estimated at 1.44 $m^3/s/km^2$ (140 cfs/sq mile) or an instantaneous discharge of 3730 m^3/s (140,000 cfs).

Because streams were ungauged or the recorders malfunctioned, discharge hydrographs for the flood period are not available for the Mackenzie River tributaries affected by the storm. Volume of flood runoff therefore cannot be directly determined for any of the tributaries. Fortunately, however, five gauging stations were in operation on the Mackenzie River and,

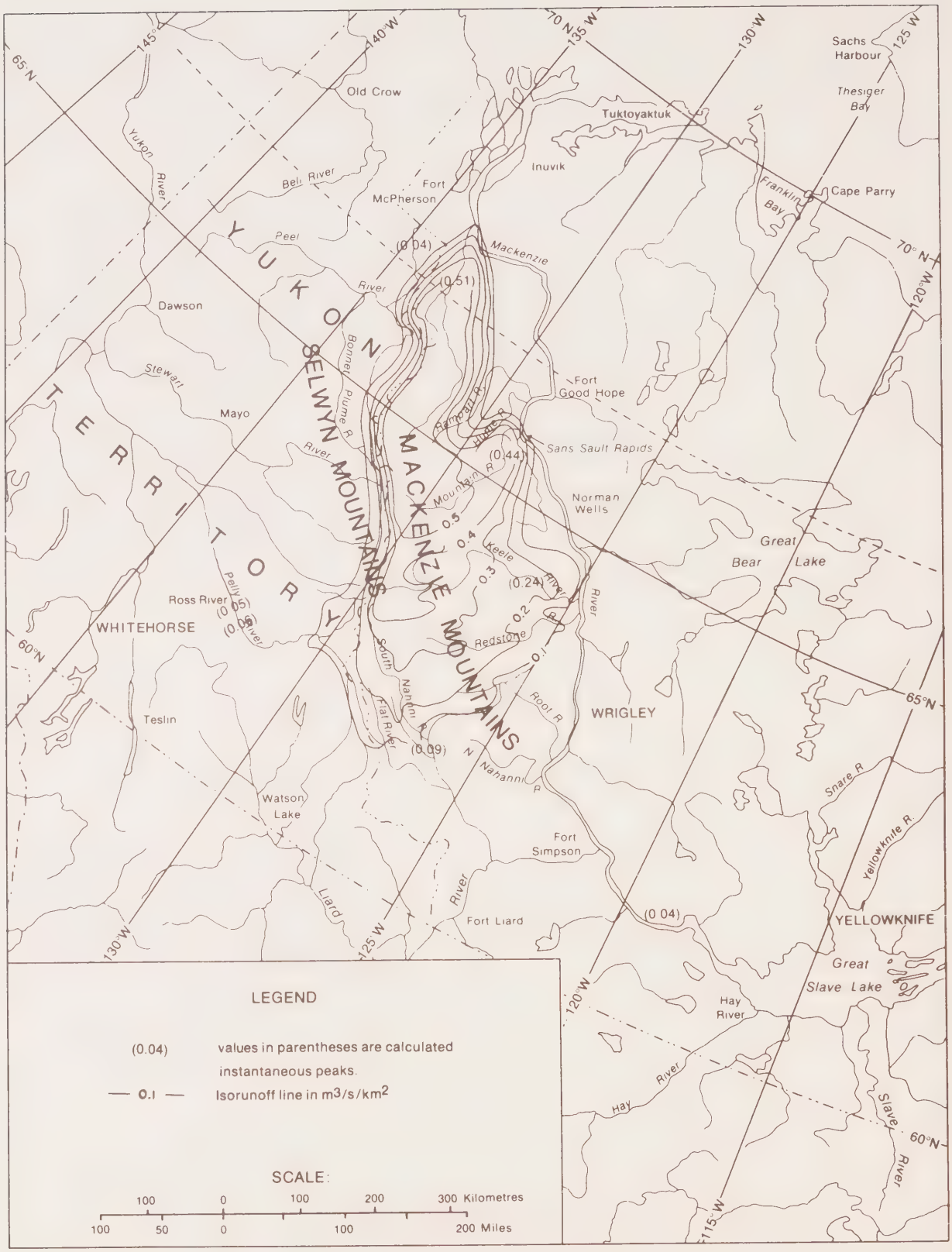


Figure 8. Isorunoff lines in $m^3/sec/km^2$ based on calculated instantaneous peak values.

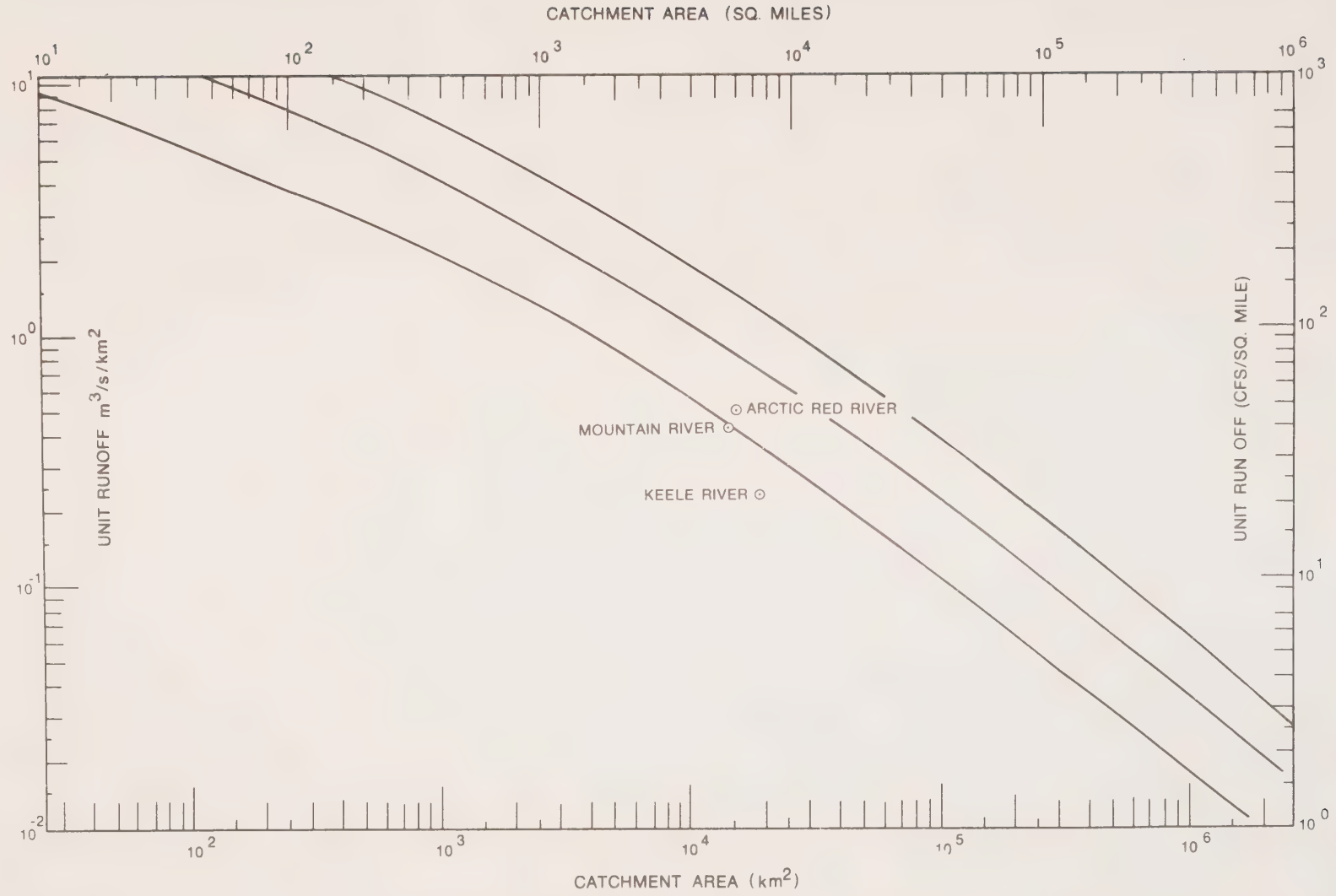


Figure 9. Creager's envelope curves for estimating peak flow magnitudes at ungauged locations.

using the discharge hydrographs of these stations, combined flood runoff volumes for some of the tributaries could be determined.

Figure 10 is a plot of the discharge hydrographs over the period 21 - 28 July 1970, for the Mackenzie River gauging stations near Fort Providence, at Fort Simpson, and at Norman Wells. The Fort Providence gauging station is located just below the outlet of Great Slave Lake and was entirely unaffected by the storm. The gauge at Fort Simpson showed a very slight rise in the hydrograph which is attributable to the slight peaking of the South Nahanni River. On the other hand the hydrograph at Norman Wells showed a well-defined peak discharge beginning about noon on July 21, 1970. The area under the bulge in this hydrograph (deducting for discharges unaffected by the storm) represents the volume of storm runoff occurring in the eastern tributaries between Fort Simpson and Norman Wells. These tributaries include the Keele, Redstone, Root and North Nahanni Rivers. The total volume of storm runoff in this reach was 1589 x $10^6 m^3$/day (5616 x 10^7 ft^3/day) of which the largest portion can be attributed to the Keele River.

Unfortunately, the stream-gauging stations on the Mackenzie River at Sans Sault Rapids and at Fort Good Hope record only water stage and thus discharge data are not available. However, the stage hydrographs for these stations are depicted in Figure 11, as perhaps in the future, flow may be measured to determine the stage-discharge relationships. The controls at these sites should be reasonably stable and thus these ratings should be applicable to the flood period. If this is the case, the reach between Norman Wells and Sans Sault Rapids can be used to determine the combined volume of runoff of the Mountain and Carcajou Rivers. Similarly, the reach between Sans Sault Rapids and Fort Good Hope could be used to determine the combined volume of runoff for the Ramparts and Hume Rivers.

As only short-term records are available for gauging stations in the area affected by the storm, a flood-frequency analysis cannot be carried out. Other means can be used, however, to provide some indication of the prevalence of important floods.

An examination of the cumulative frequency of daily stages for July at Norman Wells (Water Survey of Canada, 1970), for example, suggests that the 6.61 m (21.71-ft) stage reached on 22 July 1970 has less than a 5% chance of occurrence during the last 10 days of any July. Of greater significance is the fact that this stage was reached because of abnormal contributions from a small drainage area, principally the headwaters of the Keele and Redstone Rivers. At Fort Good Hope, the Mackenzie rose 2.9 m (9.5 ft) over the 20 - 23 July period, a unique event in the 9-year record for that location. On the Keele River, the 1970 flood (Fig. 12) far surpassed any former known high-water event, the highest previously witnessed being that which occurred in 1926 when near bank-full stage was reached (Simmons, 1970). Farther north, on the Arctic Red River, floodwaters rose 2 m (6.56 ft) around the deserted trapper's cabin known as Martin House and washed it some 100 m downstream. Such a water level may not be unprecedented, however, as in 1960 Henoch (1960) found driftwood at 14.6 m above late summer low water near Rock Cove, 16 km above the Mackenzie junction.

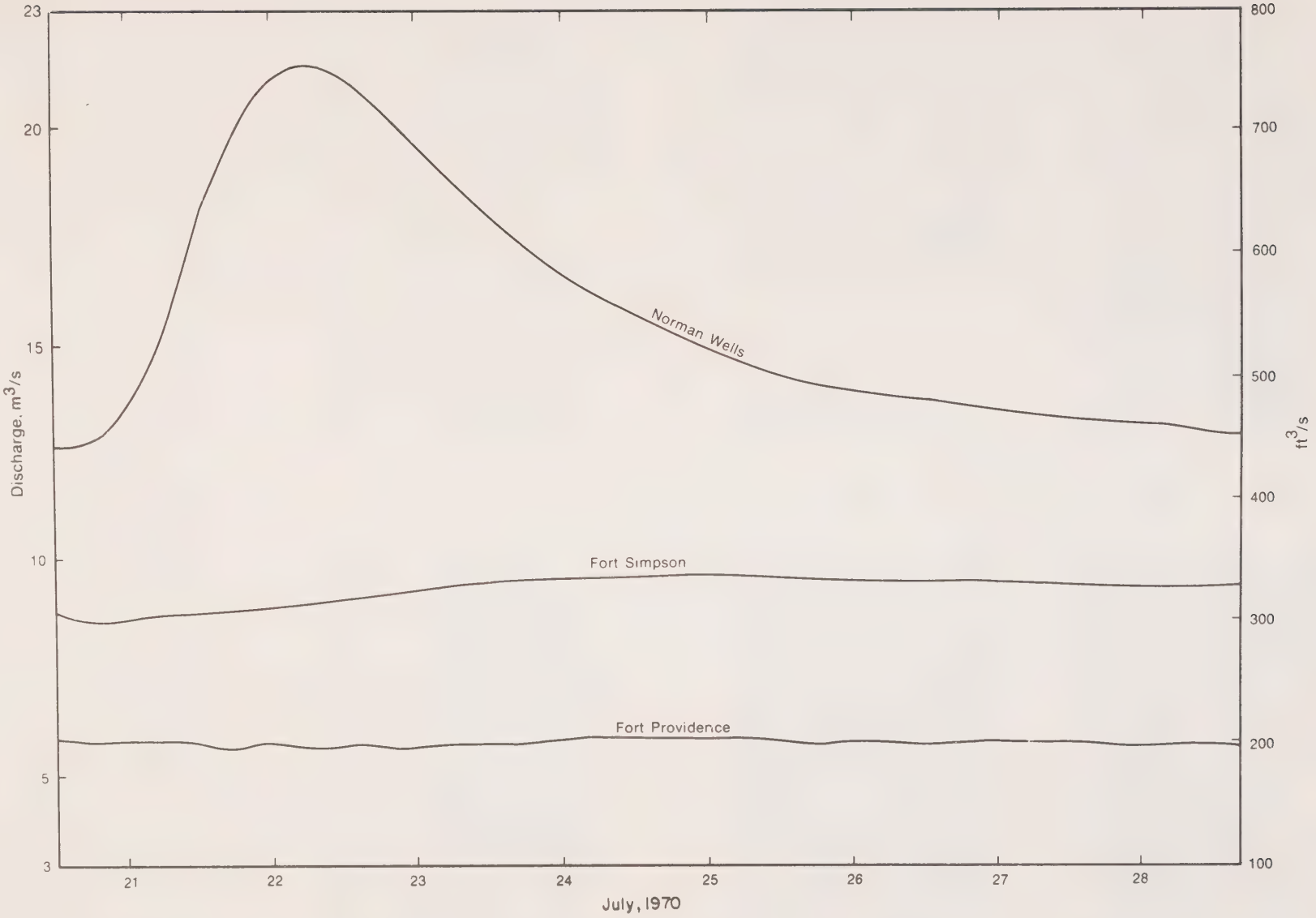


Figure 10. Discharge hydrographs for Mackenzie River gauging stations, 20-28 July, 1970.

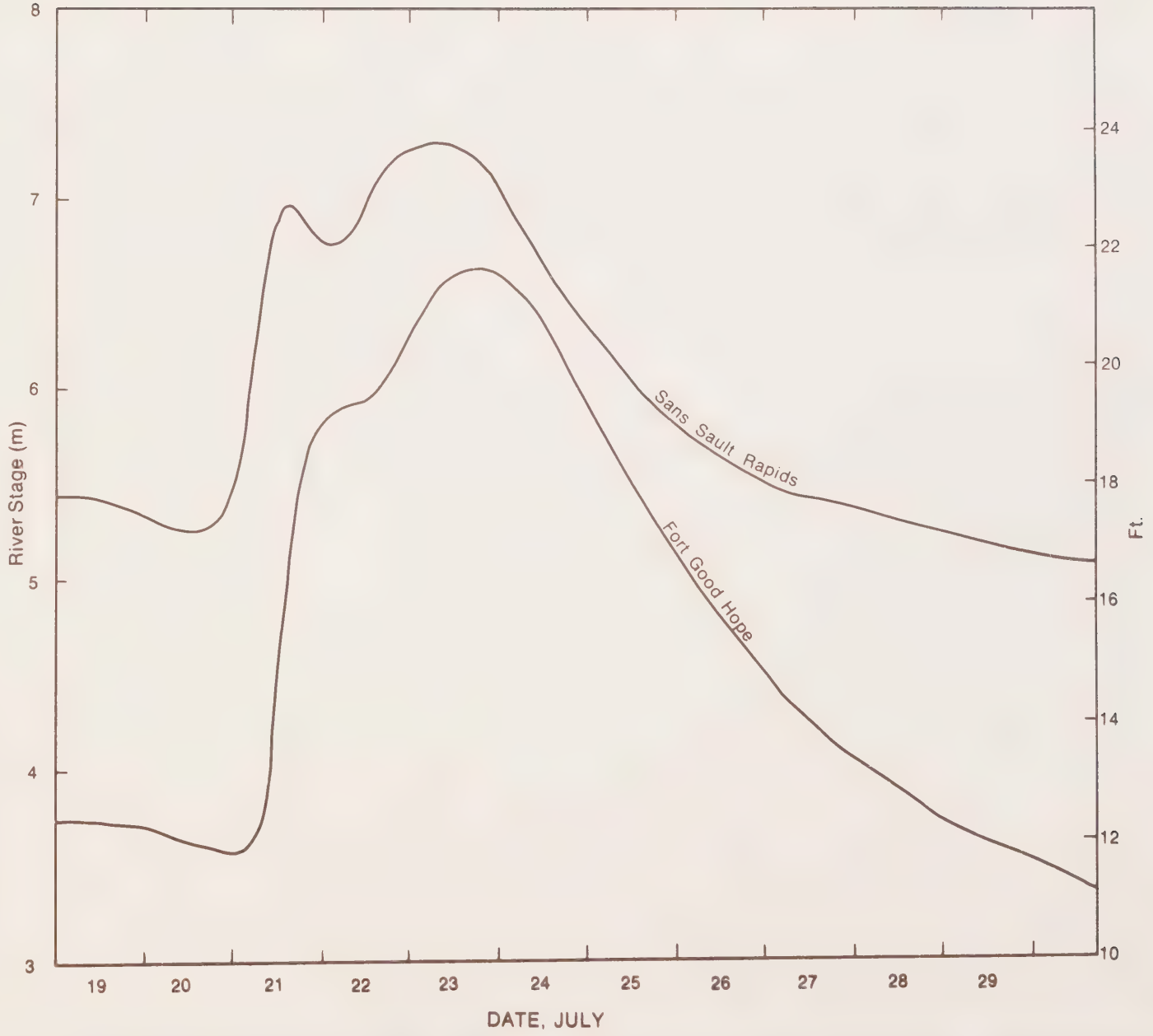


Figure 11. Mackenzie River water levels, 19-29 July, 1970.



Prior to storm, 20 July



4:00 p.m. MST, 20 July



5:00 p.m. MST, 20 July



7:00 p.m. MST, 20 July



10:00 a.m. MST, 21 July



10:00 p.m. MST, 21 July

Figure 12. Time-lapse photos of flood development at Canadian Wildlife Service cabin on Keele River, N.W.T., 55 km below its junction with the Twitya River.

Photographs by H. Armbreuwster and J. Day.

In order to add to the hydrometric data, trees flattened on the flood plains of the Arctic Red and Mountain rivers were examined and sections were cut from a number of the larger ones. Only those that were obviously bent down or broken off by the force of the flood (Fig. 13) were sectioned. Tree-ring data of the largest and oldest samples are listed in Table 3.

Tree-ring counts suggest a minimum recurrence interval of greater than 100 years and, therefore, the probability of such a flood occurring in any given year would be something less than 1%. It should be stressed that the tree samples chosen were not undercut by erosion of the soil but rather were broken off or flattened by the force of the flood waters.

Effects on Flood Plain

Aerial photography of the storm region was taken in 1949, 1950 and 1952. In 1971, portions of the storm-affected areas, mainly along the Arctic Red River, were rephotographed. These were compared with the earlier photographs to ascertain the changes which have occurred in the intervening time and, more particularly, to sort out those surface modifications that can be ascribed to the 1970 storm.

The 20-year period between photographic coverage indicates that many flood plain alterations could be the result of natural events other than the 1970 storm. Only in a gross sense, with the aid of eyewitness reports and field surveys can the 1970 storm modifications be differentiated from others that occurred in the intervening period. Examples of changes on the flood plain, bounding banks and adjacent valley slopes unrelated to the 1970 storm are extensions in vegetative cover, partial reworking of the stream bed, a number of earth flows and slumps, and some channel migration through cut-bank erosion and sedimentation. There are, however, blatant flood plain transformations (Fig. 13, 14, 15) caused by the 1970 storm that are recognizable on the 1971 photography: these are the flood pathways cut through densely vegetated slip-off slopes, meanders, and channel islands; the erosion, cutting back and, in some cases, complete removal of islands; and construction of major new levees and dune forms in braided sections.

The full length of the main Arctic Red and Mountain River channels from their mouths to their common watershed boundary was surveyed in June 1971 for lasting, visible flood damage. First indications of damage were observed approximately 48 km above the mouth of the Arctic Red River. From 48 to 113 km upstream, alluvial bed deposits had been extensively reworked and some erosion of the upper ends of the channel islands was evident.

The extent of changes wrought by the storm increased rapidly in the mid-reaches of the Arctic Red River as far as the Cranswick River junction, 201 km above the mouth of the Arctic Red River, and remained fairly constant beyond to the northern edge of the Mackenzie Mountains, a distance of another 121 km. Within the mid-reaches, 50 to 60% of the trees, shrubs and lower vegetation on the active flood plain was bent, levelled or removed with new floodways cut across the lower terraces and islands (Fig. 13). Tributary streams including Cranswick River showed little evidence of damage. In their mountain headwaters, both the Arctic Red River and Mountain River exhibit a characteristically-wide braided channel system indicative of flashy variable



Figure 13. Photos of damage to vegetation on flood plain of Arctic Red River, N.W.T., in wake of July 1970 storm. Many of the trees knocked down are 10 m or more in height.

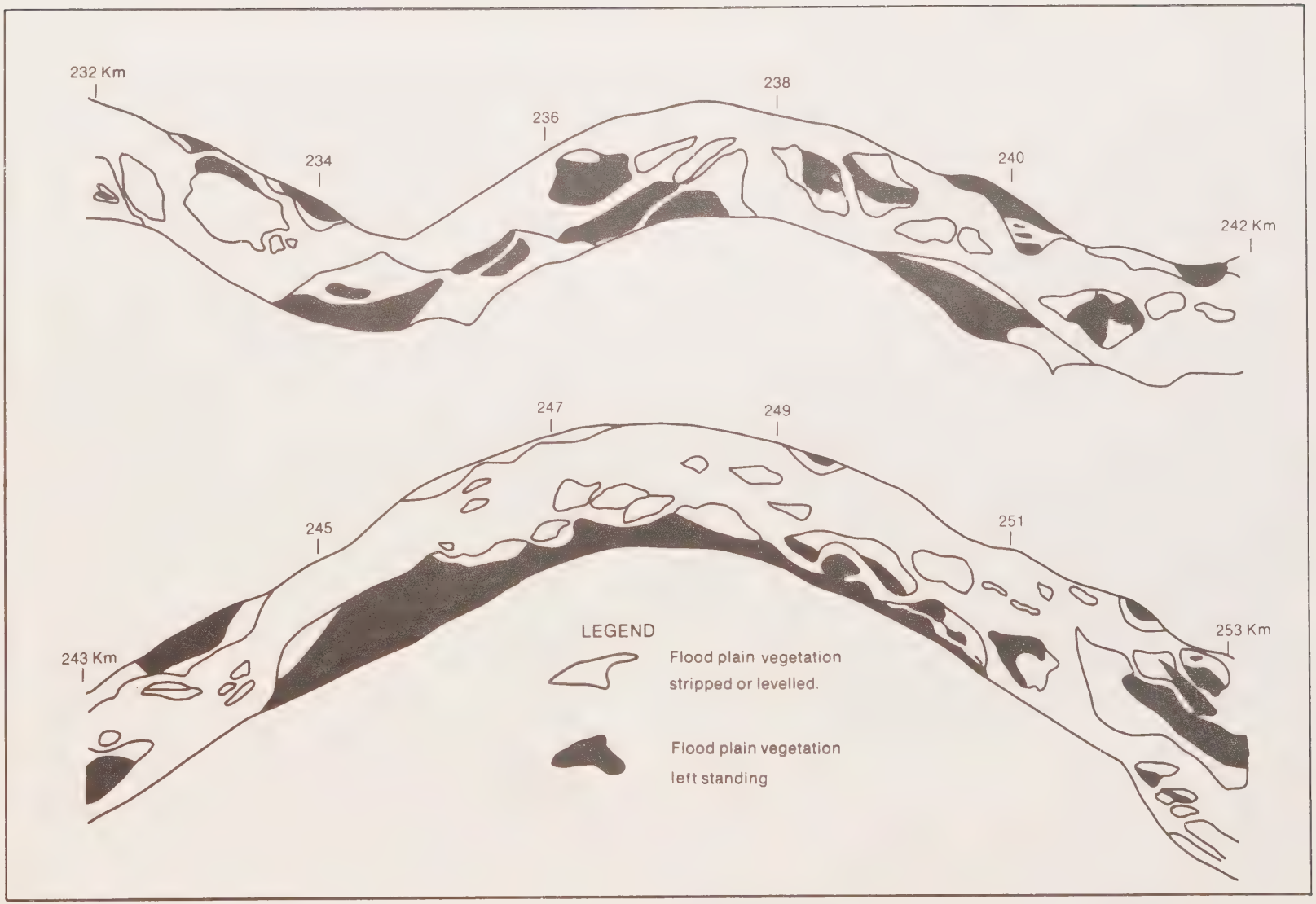


Figure 14. Typical flood plain sections of Arctic Red River showing approximate changes to standing vegetation caused by July 1970 storm. Distances are in km above mouth of Arctic Red River.

1951





1971

Figure 15. Photo comparison of Arctic Red River stretch from 260 km to 273 km above its mouth showing changes over 20-year period 1951 to 1971. Major changes in vegetative cover and channel patterns reflect effects of July 1970 storm.

flow streams with high loads per unit volume of runoff. The visible damage is limited to channel sections cutting out of the Mackenzie Mountains periphery where main channel shifting and some ponding by new dune forms is distinguishable. Upstream, the wide valleys and unconfined nature of the braided channels do not appear amenable to development of flow concentrations necessary for lasting, discernible flood damage. On the Mountain River, in fact, obvious flood plain modification by the 1970 storm is limited to the lower reaches extending for a distance of approximately 80 km above its mouth.

Summary and Conclusions

Available data suggest that the July 1970 storm was centred over the eastern slopes of the Mackenzie Mountains, directly over the headwaters of the Arctic Red River and, to a somewhat lesser extent, over the headwaters of the Mountain River. The presence of cold air aloft, vertical instability, and a synoptic-scale disturbance superimposed on thermal advection were elements in the development of the storm. Based on tree-ring data, the intensity of the storm and the flooding that followed were such that the occurrence of a similar event in any given year has a probability of less than one per cent.

The meteorological network of the Yukon and Northwest Territories appears to be inadequate for the detection and assessment of localized concentrated storm activity, such as that which occurred in July 1970 over the Mackenzie Mountains. The network, therefore, is of little value in forecasting floods on rivers draining the Mackenzie Range. Moreover, regional flood characteristics are not defined because the hydrometric network is also inadequate. The present hydrometeorological network needs to be expanded before flood forecasting on the Mackenzie Mountain tributaries becomes a rational possibility.

Some conclusions may be drawn with respect to the effects of the storm. These are as follows:

1. Malfunction of the hydrometric recording equipment is a serious problem during extreme high flows.

2. The Arctic Red River was most affected by the storm and exhibited the highest unit runoff values; using the Creager envelope curve equation, the coefficient "C" has the value 35.

3. Lesser streams lacking mountainous headwaters exhibited no flood effect.

4. A comparison of storm effects and those of break-up and ice shove show that summer storms are much more significant in causing flood plain changes on braided mountain streams than spring break-up conditions.

5. The general order of storm damage shows low terraces in the active flood plain being affected most, followed by areas adjacent to cut banks, by point bars and by channel islands.

The damage to middle and lower reaches of some west side Mackenzie River tributaries, caused by the July 1970 storm, implies hazards for pipeline crossings and construction and for other activities that could be associated

with river flood plains. Although major vegetative and geomorphic changes in 1970 were limited to stretches of the Keele, Mountain and Arctic Red Rivers, other storms could produce similar results on rivers draining mountainous areas to the north and to the south. Certainly, peak flows caused by summer storms in the Mackenzie Mountains have proven destructive in the past and will do so again in the future.

Acknowledgements

The authors wish to thank J. Day, Department of Agriculture, E.D. Fowler, Water Survey of Canada, and S. Johannsen, Arctic Mountain House, for useful discussions and information. Mrs. L. Arsenault examined tree sections and provided some of the necessary aerial photo interpretation. The work upon which this report is based was funded in part by the Environmental-Social Program, Northern Pipelines.

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Table 1. Gauging Stations

Station	Number
Arctic Red River at Martin House	10LA002
Flat River near the Mouth	10EA003
Mackenzie River near Fort Providence	10FB001
Mackenzie River at Fort Simpson	10GC001
Mackenzie River at Norman Wells	10KA001
Mackenzie River at Sans Sault Rapids	10KD001
Mackenzie River at Fort Good Hope	10LD001
Peel River above Canyon Creek	10MA001
Peel River above Fort McPherson	10MC002
Pelly River at Ross River	09BC002
Porcupine River near Bell River	09FB001
Redstone River near the Mouth	10HB001
Ross River at Ross River	09BA001
South Nahanni River above Clausen Creek	10EC001
South Nahanni River above Virginia Falls	10EB001

Table 2. Instantaneous Peak Discharges for Flood of July, 1970

Station Number	Station Name and Location	Time	Date July	Gauge Height meters (ft)	Discharge m^3/s (cfs)	Drainage Area km^2 (sq mi)	Unit Runoff $m^3/s/sq\ mi$ (cfs sq mi)
10LA002	Arctic Red River at Martin House		22	*10.58* (34.72)	*7640* (270,000)*	*15,130* (5,840)	*0.505* (46.3)
	Mountain River below Gayna River				*6230* (220,000)*	*14,270* (5,510)	*0.437* (40.0)
	Keele River below Nainlin River	0300 E+	21 +		*4530* (160,000)*	*19,220* (7,420)	*0.236* (21.6)
10HB001	Redstone River near the Mouth			Peak not Determinable			
10EB001	South Nahanni above Virginia Falls	0200	22	4.30 (14.10)	*1300* (46,000)	*14,630* (5,650)	*0.089* (8.1)
10EC001	South Nahanni above Clausen Creek	1000	22	4.57 (15.00)	*1360* (48,000)	*33,410* (12,900)	*0.041* (3.7)
10EA003	Flat River near the Mouth			Equipment Malfunction			
10MC002	Peel River above Ft. McPherson	1500	23	*7.59* (24.89)	*2890* (102,000)	*70,710* (27,300)	*0.041* (3.7)
10MA001	Peel River above Canyon Creek			No Peak Flow During July			
09BC002	Pelly River at Ross River	1300 Y	23	*2.98* (9.79)	*920* (32,500)	*19,870* (7,670)	*0.046* (4.2)
09BA001	Ross River at Ross River	1940 Y	23	*3.16* (10.37)	*405* (14,300)	*7,250* (2,800)	*0.056* (5.1)
09FB001	Porcupine River below Bell River			No Peak Flow During July			

* -Peak flow determined by slope-area survey.
E -Estimated.
\+ -Determined from Journal of Norman Simmons, Canadian Wildlife Service.
Y -Yukon Standard Time, all other times Mountain Standard.

Table 3. Tree-Ring Data from Arctic Red and Mountain Rivers

.ocation	Type	Diameter cm (in)	No. of Rings	Assumed First Year of Growth
rctic Red River kilometres (4 miles) elow Junction with ranswick River	Spruce	*35.5* (14)	135	1835
ountain River 0 kilometres (31 Miles) bove mouth	Spruce	*31.8* (12.5)	109	1861
	Balsam Poplar	*30.0* (11.8)	164	1806

BREAK-UP AND ICE JAMMING ON THE MACKENZIE RIVER, N.W.T.

by

D. K. MacKay and J. R. Mackay

Technical Report 7 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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BREAK-UP AND ICE JAMMING OF THE MACKENZIE RIVER NORTHWEST TERRITORIES

D.K. MacKay and J. Ross Mackay*

INTRODUCTION

The Mackenzie River is navigable by shallow-draft vessels over its 1,600-km length between Great Slave Lake and the Beaufort Sea (Fig. 1). The navigation season is normally from early June to late September. The waterway is actively used to supply river and arctic coastal settlements, and to an increasing extent in the past several years, oil and gas exploration needs in the western Arctic. It is the purpose of this paper to discuss some aspects of break-up and ice jamming in the river. Further data may be found in the selected bibliography.

BREAK-UP

The Mackenzie River does not break-up sequentially from south to north. Navigation from Hay River to the entrance to the Mackenzie River is often delayed by the presence of ice on Great Slave Lake. In addition, Great Slave Lake ice may run for a week or more past Fort Providence and thus retard barge traffic even though downstream portions are ice-free.

* Dr. J.R. Mackay's work is supported by the Terrain Sciences Division, Geological Survey of Canada, Department of Energy, Mines and Resources

The stretch of river from Fort Simpson to Fort Good Hope is the first to break up, and this happens nearly synchronously. The major control is Liard River water entering at Fort Simpson. Mean break-up dates are May 16 at Fort Simpson; May 17.5 at Fort Norman; and May 18 at Fort Good Hope. Break-up between Fort Providence and Fort Simpson is usually delayed by the ballasting effect of a steady flow from Great Slave Lake. The section downstream from Fort Good Hope also breaks up later, because of its more northerly position, ice jams upstream, the absence of major tributaries, and other factors.

Figure 2 shows the progress of ice clearing for six years in the 1961 to 1968 period. The break-up observations were made with the cooperation of the crews of a commercial airline (P.W.A.: Pacific Western Airlines) in their scheduled flights between Edmonton and Inuvik. It should be noted, in interpreting Figure 2, that the flight paths varied during the record period and allowances should be made for weather conditions and the interest of the observers. In spite of these limitations, Figure 2 shows the downstream rate of ice clearance with a time lag of two to three weeks between break-up in the Fort Simpson to Fort Good Hope segment, and that at Inuvik.

River stage records are not available at the time of break-up, but are available for Fort Simpson shortly after break-up.. Table 1 shows the mean rates of ice clearance at Fort Simpson as compared with the river stage for the years of record given on Figure 2. Clearly, a high stage and a rapid ice clearance are positively correlated.

TABLE 1. A comparison of mean rates of ice clearance and the order of river stage levels at Fort Simpson, Mackenzie River, N.W.T.

Year	Mean Rate of Ice Clearance km/day	River Stage Order*
1961	167	1
1962	69	2
1964	80	3
1965	76	4
1967	48	5
1968	42	6

* Highest stage = 1; lowest stage = 6.

Break-up of the Mackenzie River -- like that of many other arctic rivers -- is typically associated with a rapid rise in water level, the formation of ice jams, the impoundment of the river upstream from ice jams, the construction of high-level terraces by the dual action of ice shove and sedimentation the stranding of driftwood at all levels on the banks, and the formation of large ice-shove boulder pads in rhythmic sequence along many constricted sections. In the course of downriver boat trips, made over a period of seven summers, measurements have been taken on the limits of ice shove and the heights of driftwood borne at times by flood water or bulldozed into position above maximum flood level by ice shove (Fig. 3). Only a relative altitude can be given for the limits shown in Figure 3, because the datum used was river

level, in each summer, since the locating and measurement from bench marks was impractical. Figure 3 shows the low height of flooding between Fort Providence and Fort Simpson; a fairly uniform stretch from Fort Simpson to Fort Good Hope; a rather consistent high flooding from Fort Good Hope to above the Lower Ramparts; and then a rapid decrease to the Mackenzie Delta, which starts at Point Separation. Some of the ice jams, which cause the flooding, occur at or directly below tributary junctions. The influx of ice from rivers such as the Liard, Nahanni and Great Bear River tend to overload the transport capacity of the river, with resulting ice jams. Other sites, such as sharp bends, mid-channel islands and rock ledges may cause a local piling-up and stranding of ice. The distribution of such local pile-ups was found to be remarkably consistent from one break-up to the next, provided that the heights of flooding were comparable.

SUMMARY AND CONCLUSIONS

Break-up along the Mackenzie is neither continuous nor sequential from source to mouth. A two-week break-up period is the normal. The length of the break-up period tends to be dependent upon the river stage, with high levels favouring a rapid clearance. The maximum limit of river action (ice shove and flooding) is about 6-7 m upstream from Fort Simpson, and 10-15 m downstream.

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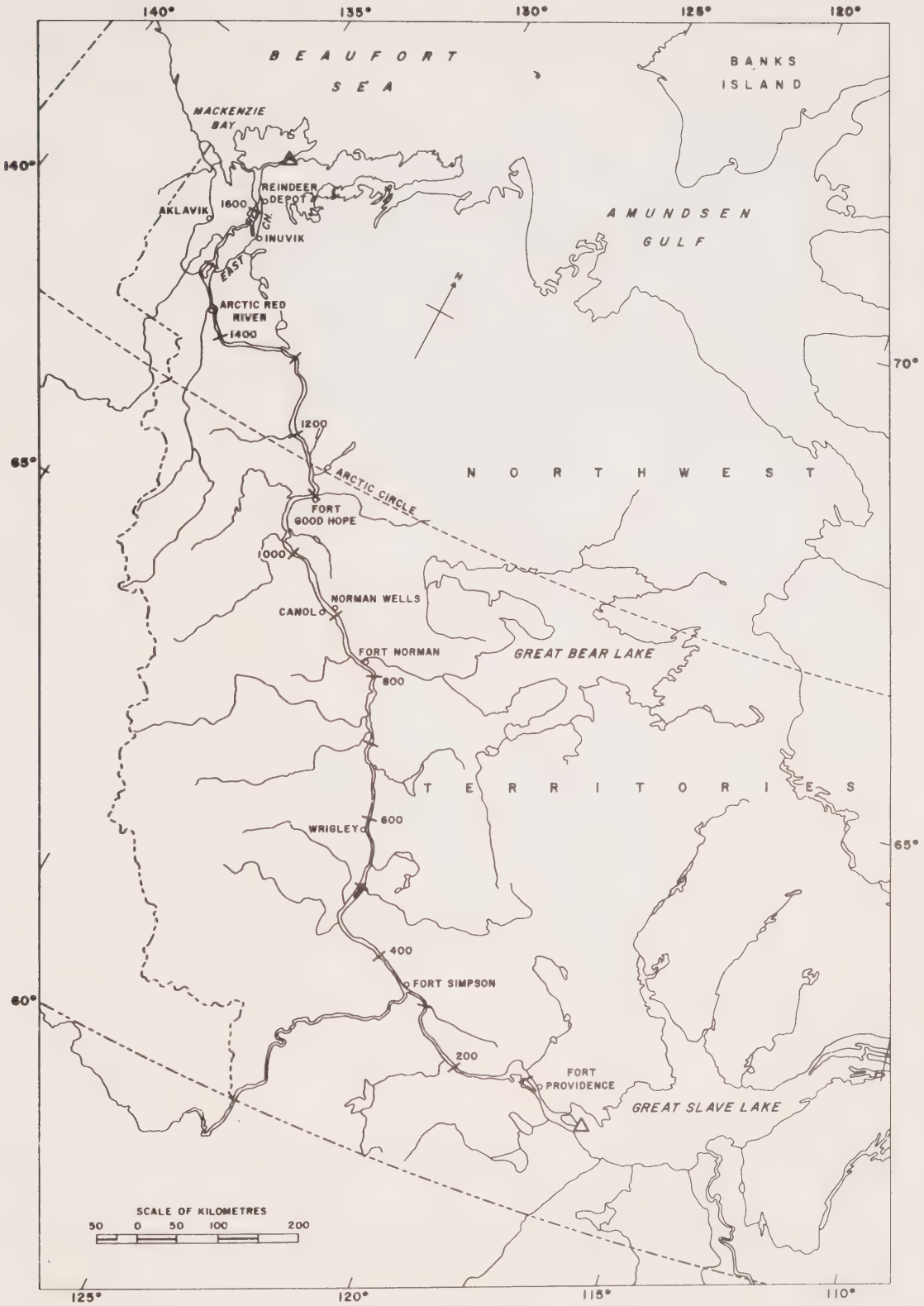


Fig. 1. Locations and distances in kilometres from the head of the Mackenzie River.

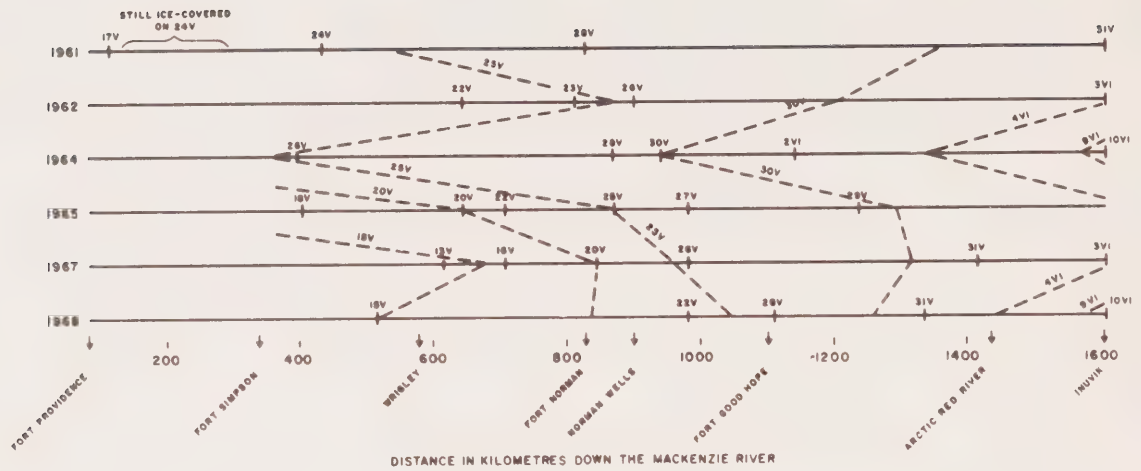


FIG. 2. P.W.A. break-up observations: progress of ice clearance

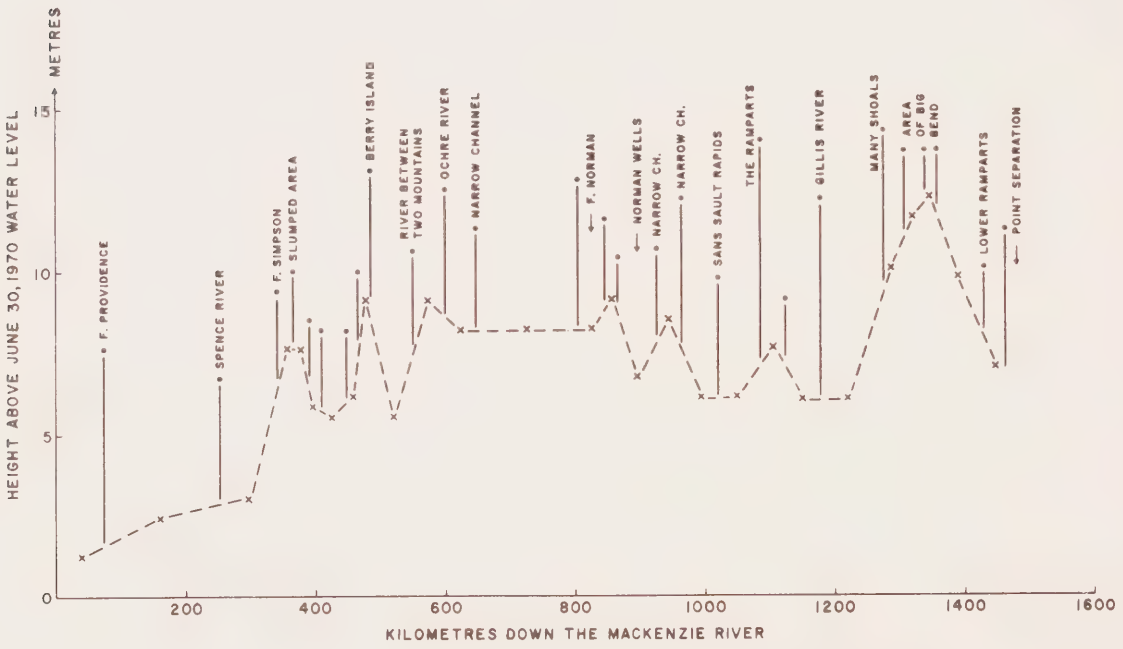


FIG. 3. maximum and minimum measured limits of ice shove or driftwood on the Mackenzie River.

LOCATIONS OF SPRING ICE JAMMING ON THE MACKENZIE RIVER, N.W.T.

by

D.K. MacKay and J.R. Mackay

Technical Report 8 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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ABSTRACT

Historical observations of ice jamming are detailed for the Mackenzie River. Such evidence of ice jamming as the distribution of river ice stranded on banks, ice shove levels and driftwood levels are reported with reference to the physical characteristics of the Mackenzie main channel. Major ice jam sites are noted and some conclusions are drawn as to the influence of the Liard River, the significance of river stage at spring break-up and the relevance of ice jam data to the location of pipeline and highway crossings. It is evident that a crossing of the Mackenzie above its junction with the Liard is much less risky insofar as break-up and ice jamming are concerned than a crossing below it.

LOCATIONS OF SPRING ICE JAMMING ON THE MACKENZIE RIVER, N.W.T.

by

D.K. MacKay and J.R. Mackay*

INTRODUCTION

In a previous study (MacKay and Mackay, 1972) we summarized ice jamming on the Mackenzie River. However, a more detailed examination of ice-jam locations and size is needed, because such ice conditions could prove significant in the selection of river crossings for oil and gas pipelines.

Underground river crossings require basic data on bed and bank scour effects, some of which are caused by ice jams. On the other hand, above-river crossings require knowledge of the height and expanse of ice jams, the processes of ice jam formation and disintegration, as well as the associated ice pressures on structures such as bridge piers.

This study does not provide river scour or ice pressure data; it does, however, point out the principal locations on the Mackenzie River where, historically, jams are known or assumed to have occurred, and where studies of scour and ice pressures might be most profitably undertaken. Also, the study indicates the relative heights of flooding and ice action above river level in a more extensive manner than previously reported and makes some suggestions about location of pipeline crossings. These data have been gathered on trips down-river by boat over eight summer seasons.

Reference to river settlements, jam locations, and other features is made in kilometres (miles) from the head of the Mackenzie River where it issues from Great Slave Lake (Fig. 1). Metric values converted from British measurement units are expressed as approximations only.

HISTORICAL OBSERVATIONS OF ICE JAMMING

Scientists and explorers who have travelled the river in the past have reported on Mackenzie River break-up and ice jamming and some have given vivid descriptions of the more dramatic events. McConnell (1890) witnessed the break-up at Fort Simpson, the junction of the Liard and Mackenzie (kilometre 330; mile 206), when on May 13th 1888 the rivers,"... icy load crept up the slopes until the crests of the hummocks peered ominously over the banks" 12 m (40 feet) above the winter ice level. A short time thereafter, "... the ice commenced

* Dr. J.R. Mackay's work is supported by the Terrain Sciences Division, Geological Survey of Canada, Department of Energy, Mines and Resources.

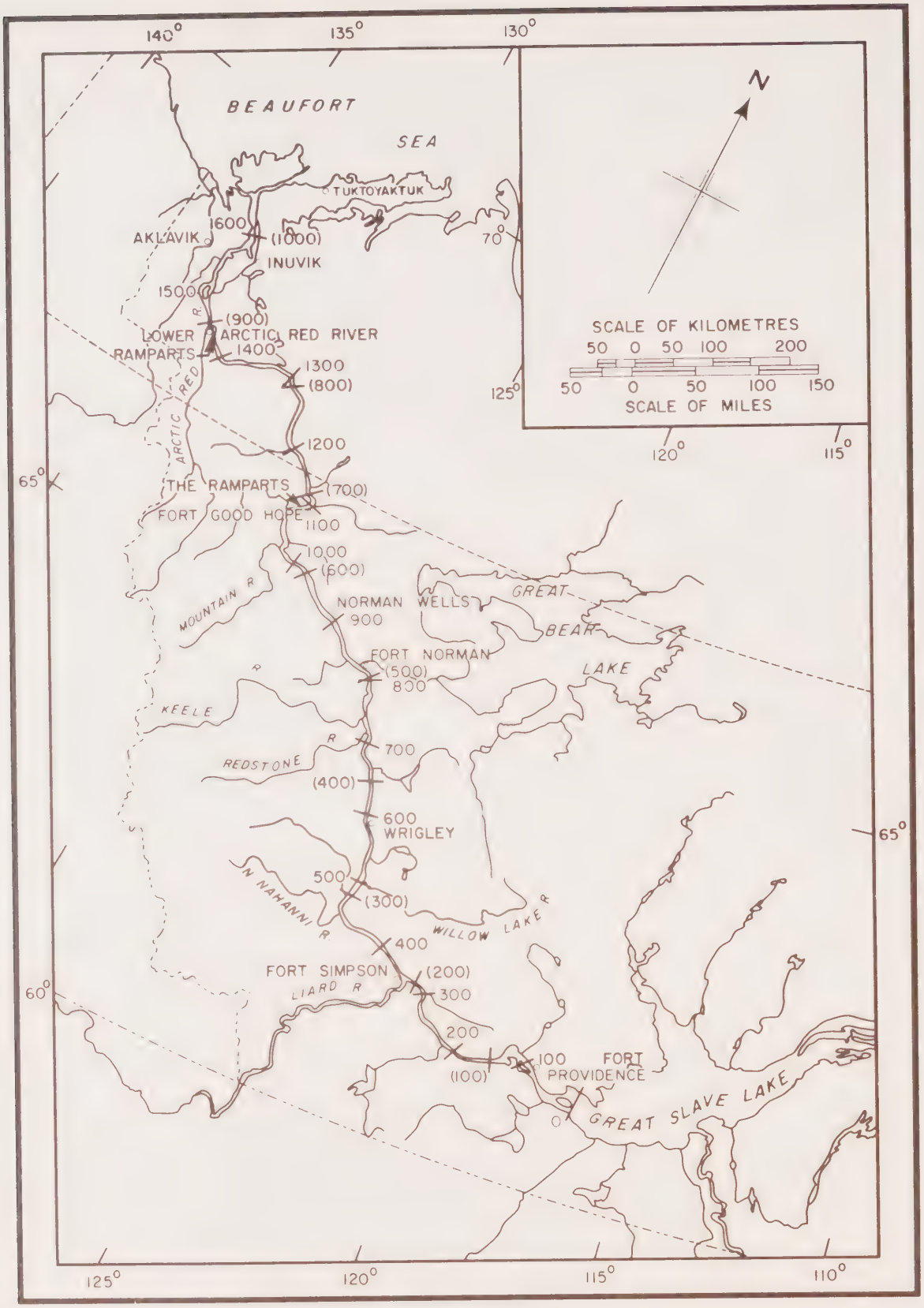


Figure 1. Locations and distances in kilometres (miles) from the head of the Mackenzie River.

to move down the river, a sure sign that the dam below was broken". In 1904, Preble (1908) was present at the same river junction when the Liard River break-up occurred on April 29th. He observed, "Its advancing flood first opened a channel nearly straight across the Mackenzie, forcing the ice with irresistible power up on the opposite bank in immense piles ... The immense volume of ice blocked the channel below the post and did not begin to move ... until the night of May 2nd, when the jam broke ...".

Jams of some magnitude are invariably associated with break-up at or just below the Liard-Mackenzie junction. The settlement of Fort Simpson, located on a 12-m (40-ft) terrace, has been flooded on at least three occasions -- once in its early years (McConnell, 1890), again in 1963 and finally in 1972 when water covered the in-town airstrip (Fig. 2) and rose to a level of 1.5 m (5 ft) in the Imperial Oil supply depot near the river bank.

Below Fort Simpson, jams are known to have occurred at a great number of sites. In 1972, for example, pilots flying out of Fort Simpson reported the head of a massive jam at kilometre 350 (mile 219), 3 km (2 miles) below Martin River with piled, jumbled ice stretching 10 to 15 km (6 to 8 miles) down-river. On May 28th, 1888, McConnel set out from Simpson down the Mackenzie River noting "The river was still full of floating ice, and wherever jams had occurred, high, cliffs of the same material lined the banks and were constantly falling in as they became undermined by the water, which had now a temperature of several degrees above freezing point. These ice cliffs at this season of the year have sometimes a continuous stretch of ten to fifteen miles along the banks ...". He specifically mentions the high cliffs of ice piled along the shore at the mouth of the North Nahanni River (kilometre 450; mile 281).

Kidd (1931) and Preble (1908) point out the abundance of shore ice farther downstream -- the latter noting on June 11th, 1904 that "All along the river more or less ice still lay on the banks, but a few miles above Fort Norman, the quantity was astounding. Many of the stranded cakes were upward of 20 feet in thickness". Although Preble suggested that the cakes "... had evidently come from the mouth of some tributary which had frozen to the bottom, and whose waters continually overflowing and freezing, had filled the valley with ice", it is more likely that such thickness are the result of river ice rafting and cementation.

At Fort Norman (kilometre 819; mile 512), Camsell (1954) described ice jamming during the 1895 break-up: "The ice kept moving for some hours and then slowly stopped. We knew that a jam had occurred at some point below. When it finally stopped altogether, the surface of the river was piled mountain-high with great blocks of ice ...". The Fort Norman settlement is situated at the junction of the Great Bear and Mackenzie Rivers where jams are not an uncommon experience. In 1964, for example, the development of an ice structure standing more than 9 m (30 ft) above winter ice level and extending 24 km (15 miles) upstream caused the worst flooding in the memory of Fort Norman inhabitants. Ice invaded the perimeter of the settled area and effectively blockaded the Mackenzie channel for a week, (MacKay, 1965). A jam of similar size and duration affected the Fort Norman settlement in 1972.

Farther downstream, at kilometre 1080 (mile 675), The Ramparts form a natural barrier to the free passage of ice during break-up. The Ramparts is a long, narrow defile cutting through lofty, perpendicular limestone cliffs



Figure 2. Aftermath of flood, Fort Simpson, May 19, 1972.

for a distance of 11 km (7 miles). Directly above it, the river channel diminishes rapidly in width, from 5 km (3 miles) to 0.4 km (0.25 miles) at the entrance, passing over a series of rapids in the intervening distance. Ice jams are a regular occurrence here and, "... the dammed-back water is stated to have risen on one occasion, over a hundred feet, and on its recession, left a boat stranded on the heights above", (McConnell, 1890); this rise of water, however, seems improbable to the authors who have examined the area a number of times. Below the Ramparts, the old Fort Good Hope settlement, located on Manitou Island, was entirely destroyed by ice and flood in the spring of 1836, following disintegration of an ice jam (Voorhis, 1930, p.75).

Occasionally, ice jams develop in the region of the Lower Ramparts (kilometre 1427; mile 892) caused in part by the movement of Arctic Red River ice into the Mackenzie channel at kilometre 1435 (mile 897). One of the writers witnessed the occurrence of moderate-sized jams at this location in 1964 and 1967.

Air observations of ice jams and related ice conditions were carried out in the period 1961 to 1968 with the cooperation of a commercial air transport carrier -- Pacific Western Airlines (P.W.A.). The observations are shown in Figure 3 for six break-up seasons. In five of these seasons, air coverage was limited to the Mackenzie River below kilometre 480 (mile 300).

P.W.A. data indicate that most jams occur within the ten-day period following the first movement of the main river ice cover (Fig. 4). The number of jams in any given year appears to be related to the river stage at the time of break-up (Table 1). River stage has also been positively correlated with rates of ice clearance (MacKay and Mackay, 1972).

DISTRIBUTION OF STRANDED ICE ON SHORE

The amount and distribution of ice lodged on the banks of the Mackenzie River following break-up varies from year to year as indicated in Figure 5. Much depends on the character of break-up: a sudden, precipitous early event and/or a rapid fall in stage generally result in heavy ice accumulation along the banks, while a placid and relatively late break-up leaves only occasional ice remnants on shore. Jamming accentuates the variability in both amount and elevation above river level of these ice deposits.

Figure 5 illustrates conditions occurring about mid-June of the years depicted. The break-up in 1970 was placid with a negligible rise and fall in water levels, the result being the grounding of only scattered ice blocks along the river. In other years, break-up occurred during a more rapidly rising and higher stage, leaving more ice on banks due to ice jamming and grounding in the river shallows.

Other factors contributing to the distribution of ice on shore are the flow of ice from Great Slave Lake into the Mackenzie; the severity of winter climatic conditions bearing on river ice thickness; the timing of break-up on tributaries; the hydrometeorological conditions giving rise to and present during the break-up season; and most significantly, the physical characteristics of the river itself.

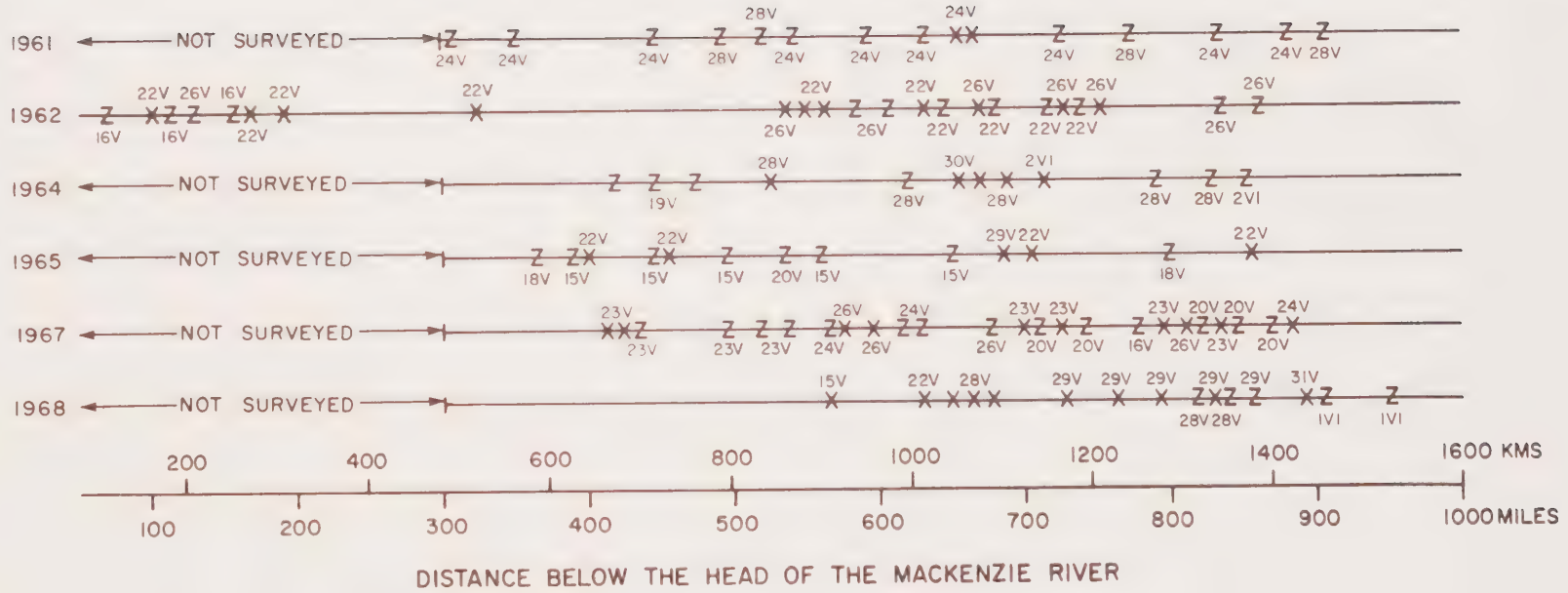


Figure 3. P.W.A. break-up observations: ice jams (X) and broken ice conditions (Z)

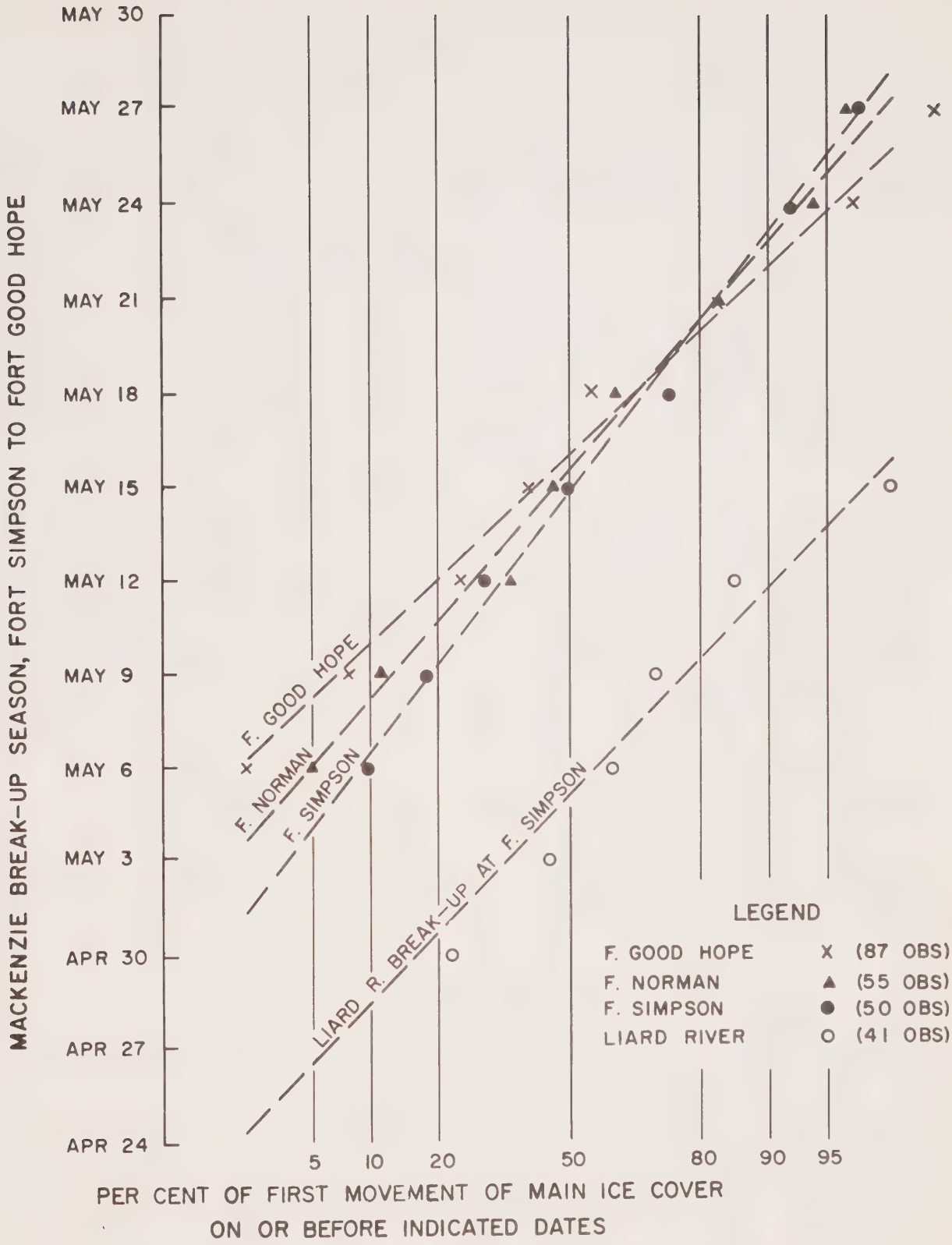


Figure 4. Probability characteristics of first movement of main ice cover at three locations on the Mackenzie River and one location at the Liard River mouth.

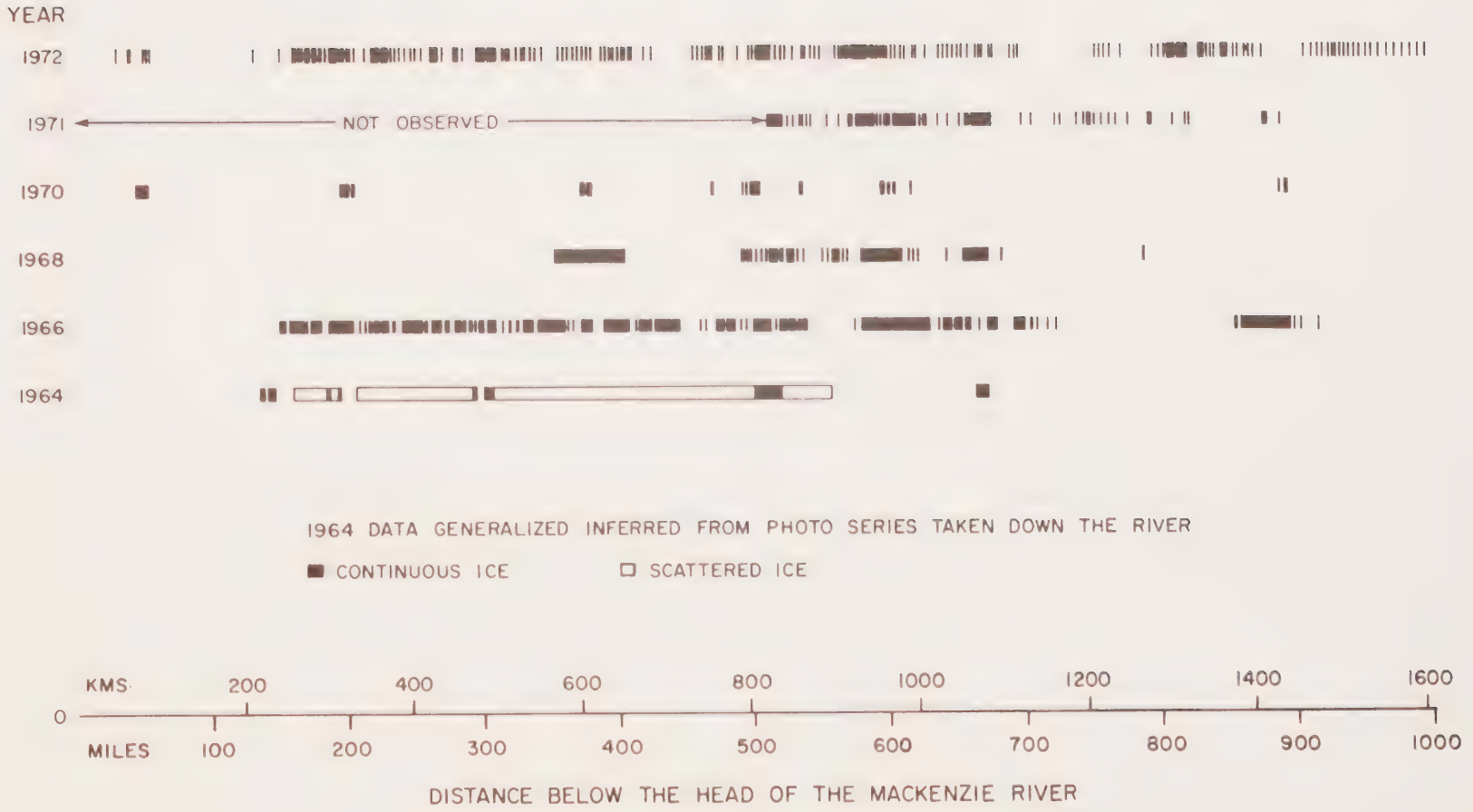


Figure 5. Distribution of ice stranded above banks of Mackenzie River in early June.

THE MACKENZIE MAIN STEM: PHYSICAL CHARACTERISTICS AND ICE JAMMING

The general physical relations between river ice and channel morphology have been examined previously (MacKay and Mackay, 1972). Here, the description embodies an overview of the whole river with emphasis on specific locations and conditions that affect the river ice regime in total, but most particularly, those phases related to ice disintegration.

A. Kilometre 0-480; Mile 0-300 (Fig. 6).

The entrance to the Mackenzie River is split for a distance of 27 km (17 miles) before flow enters Beaver Lake, a wide section of the river which acts as an ice growth stagnation and ponding area. Ice from this section and from Great Slave Lake, driven by the vagaries of wind and slow current, then enters the narrowing body of water known as the Providence Rapids where tumbling ice wreckage is funnelled into the Providence Narrows (kilometre 72-80; mile 45-50).

Evidence of ice shove reaches 7.6 m (25 feet) above datum at the upstream end of Providence Island, and according to local information, has reached higher levels along the face of the 11.6-m (38-ft) terrace on which Fort Providence is situated. The area below is one of moderate jamming, stretching 96 km (60 miles) down through the intricacies of an island-strewn channel to where the Mackenzie River begins to widen as it moves into Mills Lake. Jamming in the Providence region is caused by the funnelling of ice into a narrow channel at high current speeds and is accentuated in the townsite area by a gravel and boulder ledge extending out from Providence Island towards the town, and by the island obstructions below.

Mills Lake, (kilometre 104-126; mile 67-79), is a significant ice growth and ponding area where, under conditions of spring high-water, roughly 260 km^2 (100 sq miles) of ice wreckage can be accommodated. Here, ice moving in from Great Slave Lake and the upper Mackenzie River may lie for some time, subjected by wind and current to forces of abrasion and grounding and to melting temperatures. Much ice deteriorates or disintegrates in the lake for, in fact, there is little downstream evidence of jamming for another 100 km (60 miles).

In the section from Mills Lake to the Head of the Line (kilometre 224; mile 140), ice shove is relatively constant and does not exceed 3 m (10 ft) above datum. Below the Head of the Line, the tapering channel contracts in width to as little as 200 m (220 yd) with a complementary rise in the limits of ice push and driftwood to 6.7 m (22 ft). One obvious jamming area is directly above Browning's Sawmill (kilometre 270; mile 169), where the Mackenzie bends and a promontory at the mouth of the Spence River projects into the channel from the right bank. Jams may occur at other points in this section where shoal areas caused by rock ledges, boulders and tributary stream deposits, constrict the free passage of ice in the channel.

From Browning's Sawmill to the Liard-Mackenzie junction, the river gradient increases and the channel gradually widens. This stretch exhibits no significant evidence of jamming as ice shove levels remain between 3-4 m (10-13 ft).

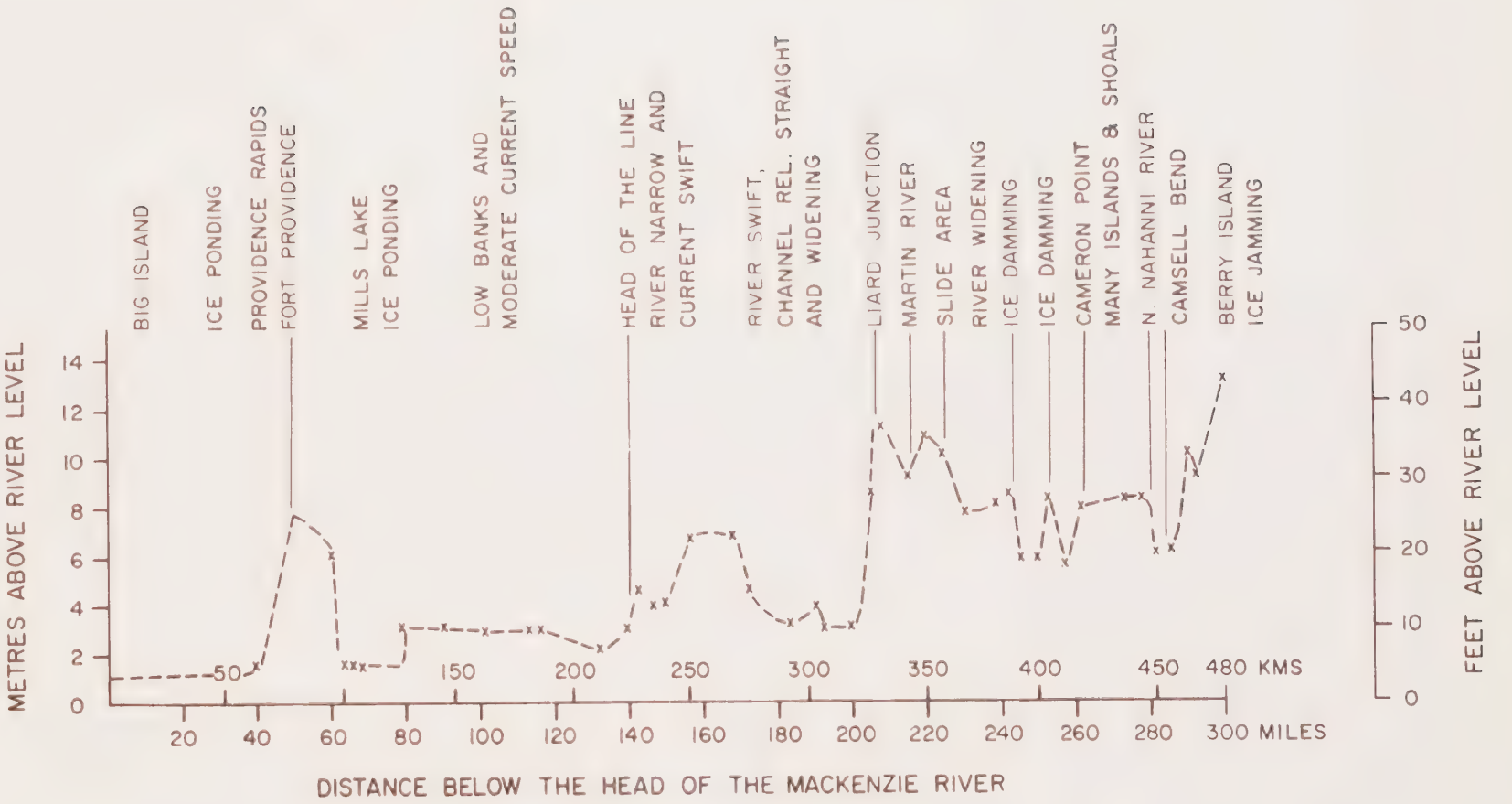


Figure 6. Mackenzie River, kilometre 0-480 (mile 0-300) combined ice shove and driftwood limits above June 30, 1970, water levels.

The waters of the Liard River have a profound effect on the break-up of the Mackenzie River. During the break-up period, the flow contribution of the Liard River to the Mackenzie River is more than half the total Mackenzie flow past Fort Simpson (kilometre 333; mile 208).

Liard break-up occurs on a rapidly rising stage exerting great pressure on the Mackenzie ice cover, differentially lifting it and producing a series of jams for many miles down-river. Ice shove and driftwood levels indicate major ice dams have developed in past years in at least seven locations between Fort Simpson and Berry Island (kilometre 480; mile 300).

At and directly below Fort Simpson, flooding has reached 12 m (40 ft). Both historical and physical evidence point to jams in this stretch which probably develop in response to Liard ice overloading the Mackenzie channel and grounding on the shoal areas and islands at kilometre 336 (mile 210), and down. At the Martin River mouth, the cabin of Stanley Isaiah, located on 9 m (30 ft) terrace was flooded in 1972 for the first time in the 50-year period that Mr. Isaiah has been resident there (personal communication).

In the 8 km (5 mile) stretch below kilometre 352 (mile 220), landslides and massive slumping related to the presence of ground ice has constrained the westerly sweep of the deep-water channel and, in conjunction with islands and shoals, has led to jam formation. At kilometre 403 (mile 252), trees have been uprooted and pushed over within the last year or two at levels of 8.5 m (28 ft) above datum by the force of ice movement. Down-channel, ice damming has occurred off the mouth of the North Nahanni (kilometre 450; mile 281), probably due to the lodgement of ice in its wide and shallow delta which projects into the flow of the main river, and to the sharp northerly swing of the Mackenzie at Camsell Bend (kilometre 456; mile 285). Eight kilometres (5 miles) below Camsell Bend, the action of ice 10 m (33 ft) above river level is apparent on channel banks and on Round Island in mid-stream.

B. Kilometre 480-960; Mile 300-600 (Fig. 7).

Berry Island (kilometre 482; mile 301) is an obvious ice damming site; driftwood and ice shove levels rise to 13.1 m (43 ft) above river level on its upstream face, but lower rapidly along its eastern flank. Below Berry Island, the level of ice action lowers as the Mackenzie widens and passes among a series of islands. In the approach to the River Between Two Mountains (kilometre 533; mile 333), steep boulder shores and ice-formed boulder ridges attest to the force and height of ice movement. Jamming occurs near kilometre 552 (mile 345), where ice has pushed to 11.6 m (38 feet) up the banks. A short distance below Wrigley (kilometre 576; mile 360), the delta of the Ochre River (kilometre 600; mile 375) combines with a rocky shoal on the opposite side of the Mackenzie channel to cause jamming and ice push to 12.5 m (41 ft).

Downstream, ice and driftwood levels are maintained at a minimum of 8.2 m (27 ft) above datum with an increase to 11.3 m (37 ft) at kilometre 643 (mile 402), where the river courses through a narrow channel, 0.8 km (0.5 miles) in width, between steep, high banks. In the steep-banked sections which are predominant through to Fort Norman (kilometre 819; mile 512) and beyond some evidence of ice action is lost by slumping and sloughing of materials along the banks. Directly above Fort Norman, ice shove and driftwood levels rise to 12.8 m (42 ft), complementing historical data of ice jams in the region.

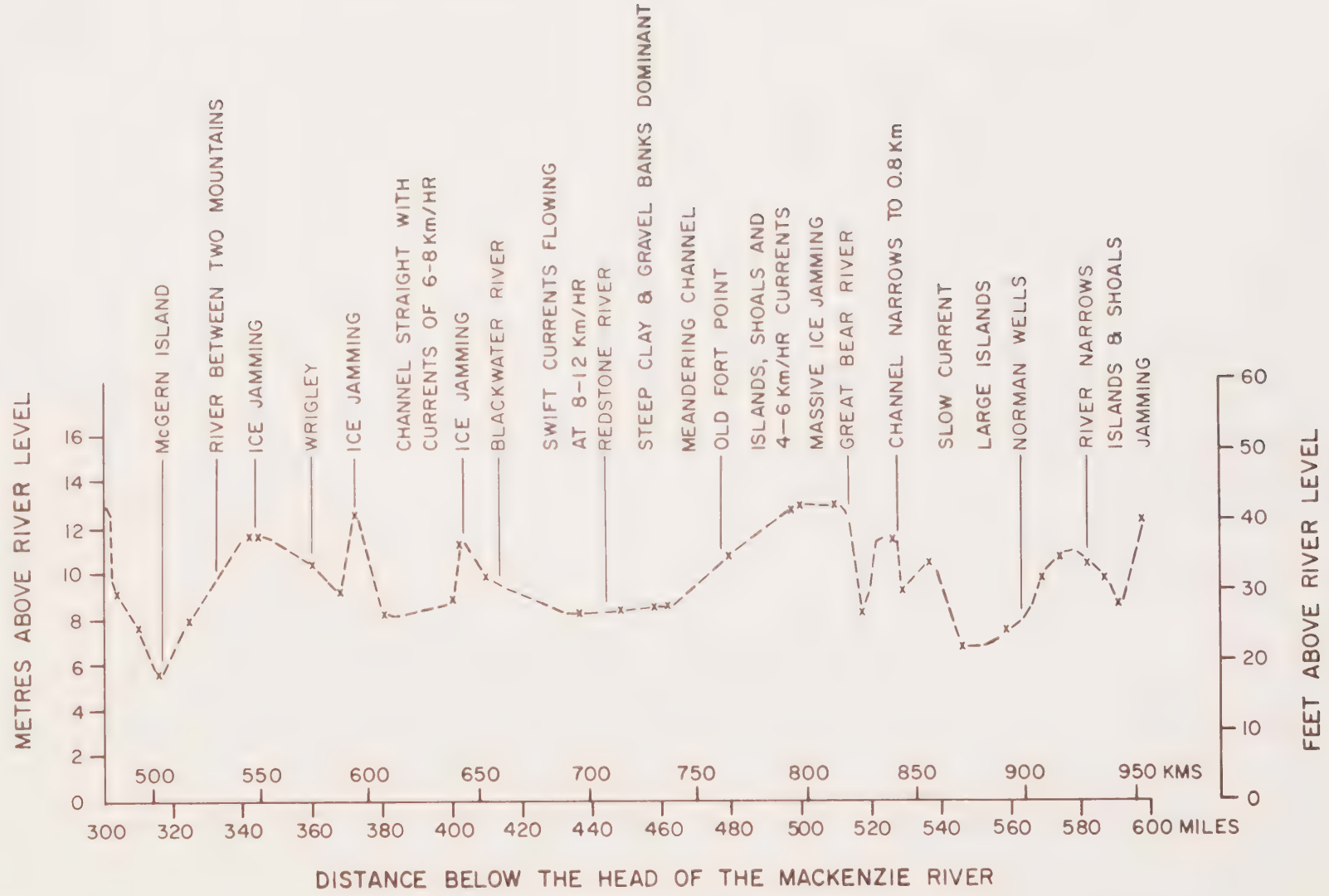


Figure 7. Mackenzie River, kilometre 480-960 (mile 300-600) combined ice shove and driftwood limits above June 30, 1970, water levels.

The Great Bear River which enters the Mackenzie at kilometre 821 (mile 513), provides relatively stable inflow even in spring because of the control exercised by Great Bear Lake. Its ice cover, however, contributes to the development of ice jams off its mouth. Between the Great Bear River and kilometre 830 (mile 519), an extensive widening in the channel militates against high ice-shove levels but, over the next few kilometres, attenuation of channel width results in an increase to 11.1 m (38 ft). Over the course of the next 80 km (50 miles) the river flood-plain tends to widen with a consequent lowering trend in the levels of ice action. In the Norman Wells region (kilometre 896-912; mile 560-570), the flood-plain extends to 5.6 km (3.5 miles), but it is strewn with shoal areas and islands which are often overridden by ice in spring. From Norman Wells to kilometre 960 (mile 600), the width of the Mackenzie channel is compressed at two points -- kilometre 928 (mile 580) and kilometre 960 (mile 600) -- and both exhibit the effects of ice jamming.

C. Kilometre 960-1472; Mile 600-920 (Fig. 8).

Over this stretch of the Mackenzie River, ice shove and driftwood heights are maintained at conspicuously high levels. Ice jamming occurs at many locations, some of which are of major significance in the spring break-up process.

In the Carcajou Ridge area (kilometre 976; mile 610), where the narrowing Mackenzie swings westward between steep high banks, jamming and flooding have reached 12.2 m (40 ft) above datum. Down-channel from the ridge, a drop in the level of ice action is evident as flow is split by the islands lying off the mouth of the Carcajou River. The Mackenzie then passes over the rock ledges of the Sans Sault Rapids (kilometre 1008-1024; mile 630-640) where the level rises on the Dumit Islands, the upstream face of the principal island being exposed to ice tumbling through the major stretch of rapids. The rapids of the Sans Sault, in point of fact, are important in the disintegration of ice moving down-river and, in consequence, tend to reduce jamming for roughly 29 km (18 miles) below.

The Ramparts (kilometre 1078-1090; mile 674-681) constitute one of the greatest geomorphic obstructions to the progress of ice clearance on the Mackenzie River. As previously mentioned, jams are an annual feature here. Above the entrance, ice shove and driftwood limits suggest recent jamming and flooding to 14 km (46 ft) above datum, although there is some historical indication that flooding has topped the cliffs of the Ramparts.

The next 80 km (50 miles) of river exhibit no major surges in ice and driftwood levels in spite of the deep-water channel weaving from bank to bank among numerous islands and shifting sandbars. At kilometre 1176 (mile 735), a distinct increase in levels suggests ice jamming in previous years. The condition upstream from this jam location is repeated over the next 80 km (50 mile) downstream section. Then, as the river's path swings through 90° to run west for roughly 110 km (69 miles), ice shove and driftwood limits increase and are sustained in the range of 10-14.3 m (33 to 47 ft). From kilometre 1376 (mile 860), through the Lower Ramparts to the Mackenzie Delta, the evidence of ice reworking the banks is apparent more than 9 m (30 ft) over datum with occasional fluctuations and a distinct lowering in level as Point Separation and the Delta are approached.

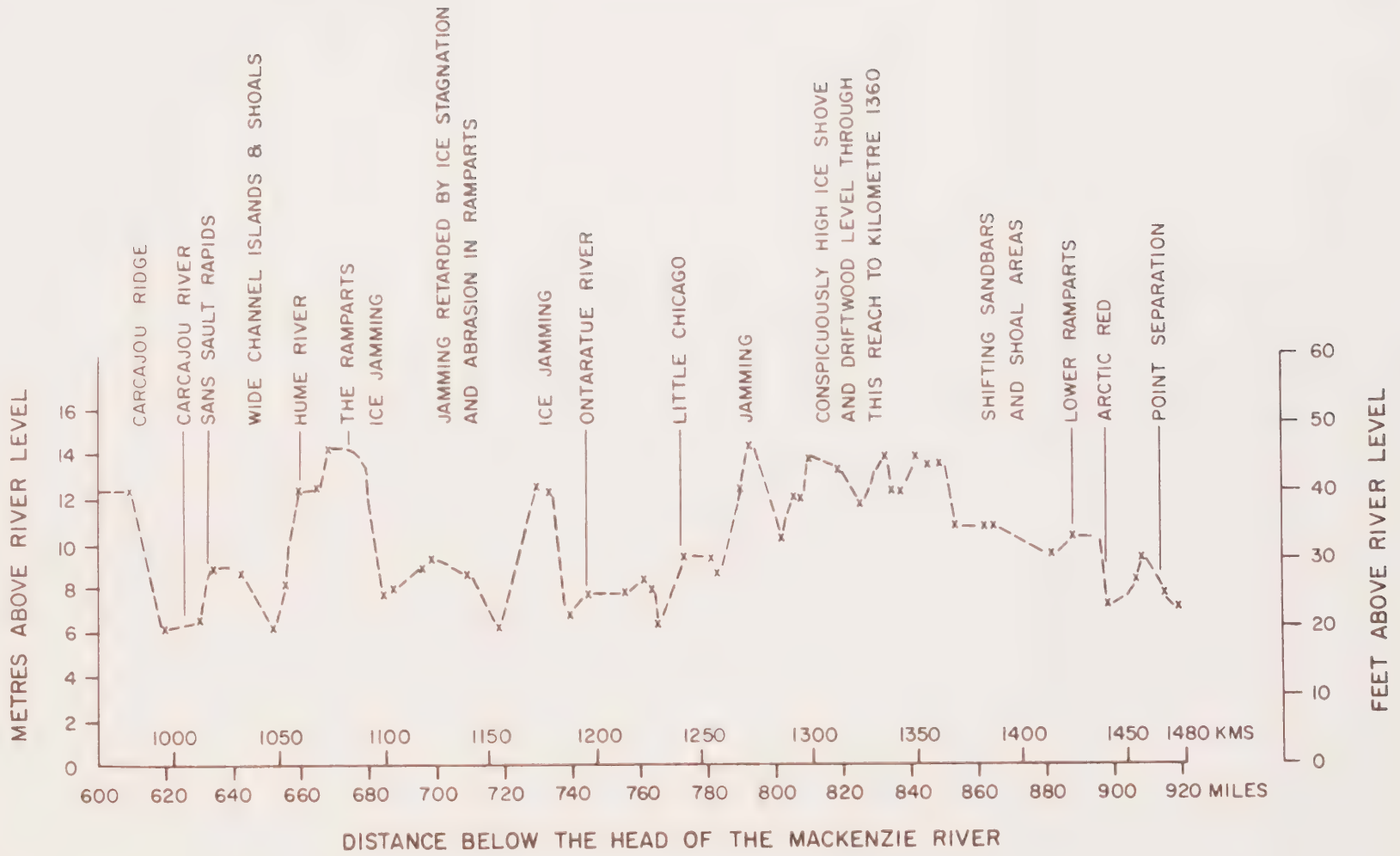


Figure 8. Mackenzie River, kilometre 960-1480 (mile 800-920) combined ice shove and driftwood limits above June 30, 1970, water levels.

SUMMARY OF ICE JAMMING

Ice shove-driftwood limits and vegetation trim lines of the Mackenzie River trend to higher levels with increasing distance from the head of the river (MacKay and Mackay, 1972). Figure 9 displays cumulative percentual deviations plotted from the mean height of ice shove-driftwood at jam locations. The resulting curve indicates that ice jams get higher downstream, heights being consistently below the mean (descending curve) to kilometre 472 (mile 295), and generally above the mean (rising curve) over the remaining distance down-channel to the delta. Intuitively, there is an expectation of a progressive downstream rise in jam heights because of increasing discharge and channel ice loading.

Ice-pushed features are often separated from river datum by the growth of trees and shrubs such as willow, poplar, and birch. Tree-ring counts, dating minimum time to ice-pushed ridge development, suggest little or no age coincidence among the highest ice features along the Mackenzie River. In a 340-km (210 mile) channel stretch (kilometre 1120-1460; mile 700-910), for example, minimum age of the highest ridges varies from six to more than sixty years. Implicit in this age variation, are the constraints imposed on the number of major jams in any year, which can be formed from the ice cover in the main channel and from the ice contribution of tributary streams. In other words, ice cover disintegration can only support the development of a limited number of major jams because the supply of ice required for a single large jam would constitute the total ice cover of a long stretch of river.

Possible sites where major jams are known or assumed to have developed are listed in Table II. One characteristic of the majority of Mackenzie River ice-jam locations is the constriction of the channel. The mean channel widths at jams is 1.3 km (0.81 miles) as compared to the mean width of the Mackenzie River as measured at 16 km (10 mile) intervals of 2.6 km (1.36 miles). In fact, only two of twenty-two jam locations exceed the mean width of the river. One of these is Berry Island, where a narrow deep-water channel deflects east past the face of the island and where the channel to the west is island-strewn with shoal areas. The other is at the junction of the Great Bear with the Mackenzie River, where shoals off the tributary mouth in conjunction with Windy Island, Great Bear Rock and the ice cover of both rivers often cause ice jamming.

CONCLUSIONS

There is a considerable difference between the ice jamming characteristics of the Mackenzie River from Great Slave Lake to the junction with the Liard River and below its junction with the Liard. In the 333 km (207 miles) above the Liard junction, the Mackenzie River is relatively stable of flow, somewhat late in break-up, and has low ice shove-driftwood limits with few major jam sites. At and below the Liard junction, Mackenzie River break-up generally occurs earlier on a more rapidly rising stage with significantly higher levels of ice shove-driftwood and numbers of jam locations. The flow from the Liard River more than doubles that of the Mackenzie River, putting tremendous pressure on its ice cover; possibly when shore leads are ill-developed and ice still shorefast in sections. The poor state of the Mackenzie River ice-cover decay combined with the great ice and water inflow from the tributaries contribute to high ice shove-driftwood limits and ice jamming from Fort Simpson on down to the Mackenzie Delta.

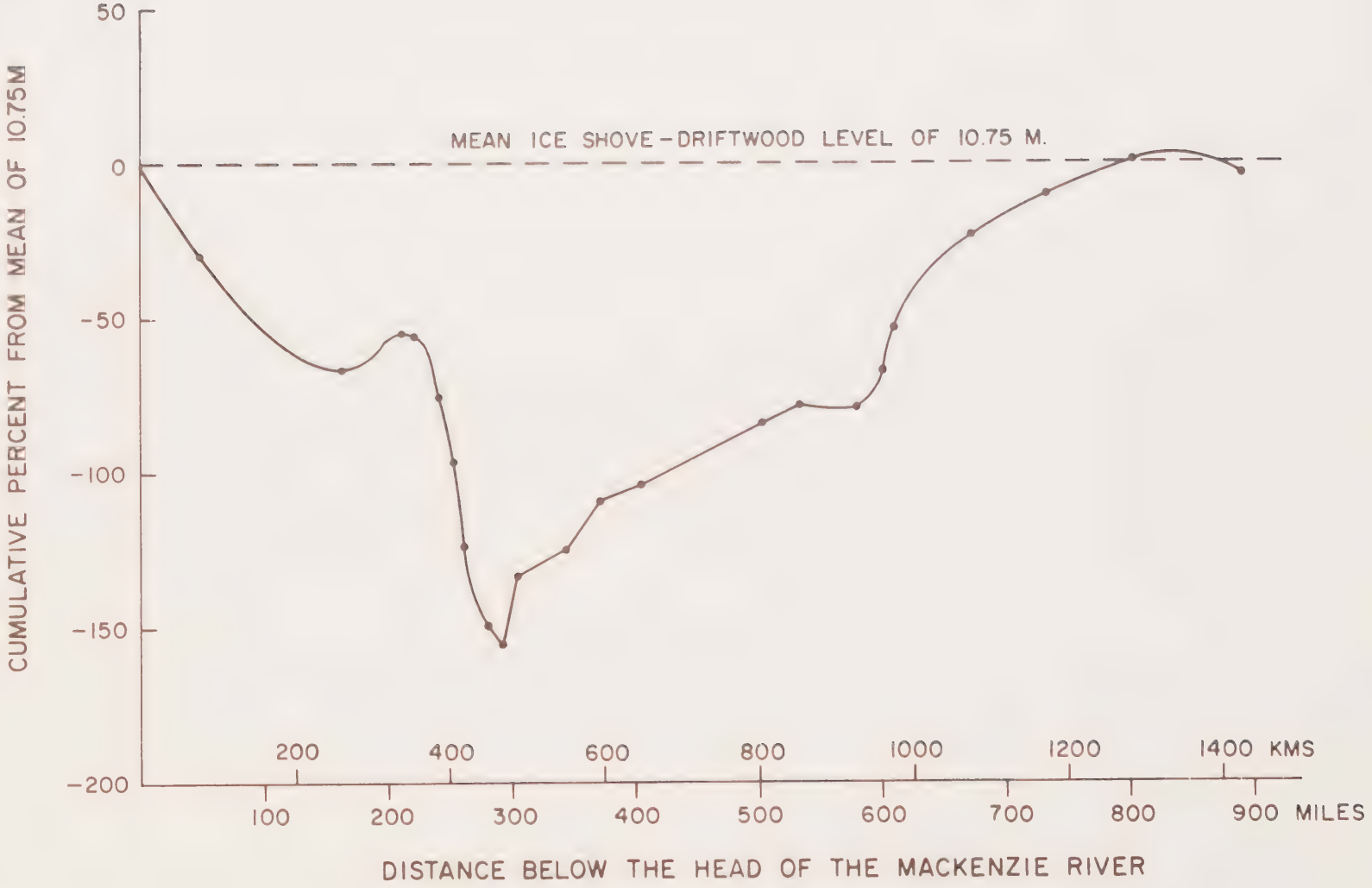


Figure 9. Cumulative percentual deviations from the mean of ice shove - driftwood levels reached at assumed jam locations listed in Table II.

In high-water years, the size of ice jams may increase but their number decreases; conversely, in low-water years, jams increase in number but their size is limited.

The process of ice jamming may accelerate channel ice clearance through ice grounding during both the rising stage of jam development as well as during the recession stage following rupture of the jam. The abrasion of ice in the jamming process is another factor abetting the disintegration of the spring ice cover.

Ice jams recur quite regularly at a number of sites; while at others, recurrence may be infrequent or rare. New sites develop as the harmonics of channel flow are changed by events such as slumping of banks, land-slides, ice jams and normal fluvial processes of erosion and sedimentation. Because of these possibilities, or other random happenings, a reach of river or a portion of it, may have an aggrading character in one year and be subject to scour effects in a later one.

Ice jams and the high levels of ice action along the banks of the Mackenzie River below the Liard River junction indicate the existence of hazardous conditions for both underground or over-river pipeline crossings. The prevalence of ice jamming causes unknown and constantly changing river scour and fill conditions; the height of jamming and unknown ice pressure factors create formidable problems associated with bridging the river for both pipeline and highway construction.

It is evident that crossing the Mackenzie River above the Liard River junction would significantly reduce the magnitude of risks associated with break-up and ice jamming. There, relatively stable flow at break-up limits ice shove and flood levels although back-water effects may influence stage directly above the confluence of the Liard and Mackenzie Rivers. Similarly, pipeline and highway crossings upstream from Point Separation might reduce ice action risks by selecting sites in as close proximity to the Mackenzie Delta as is reasonably possible.

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TABLE I

A Comparison of Ice-Jam Frequencies,
Wrigley to Arctic Red River,
and the Order of River Stage Levels
at Fort Simpson, Mackenzie River, N.W.T.

Year	No. of Jams	River Stage Order*
1961	2	1
1962	7	2
1964	5	3
1965	5	4
1967	10	5
1968	10	6

* highest = 1

lowest = 6

TABLE II

PROBABLE SITES OF ICE JAMMING - ON THE MACKENZIE RIVER, N.W.T.

Location at km (mile)	Ice or Driftwood Strand Level in m (ft)	Channel Width (Water Surface) in km (miles)	Remarks on Possible Causes of Jams
Fort Providence 77 (48)	7.6 (25)	0.6-1.1 (0.4-0.7)	Rapids above rock ledge and island maze.
Kilometer 250-269 (Mile 156-168)	6.7 (22)	0.1-1.0 (0.4-0.6)	Projection of promontory at Spence River, narrow channel.
Kilometre 336 (Mile 210)	12.2 (40)	1.6-1.9 (1.0-1.2)	Liard ice grounding in shoal areas and on islands.
Kilometre 352-360 (Mile 220-225)	10.7 (35)	1.0-1.9 (0.6-1.2)	Landslide, Liard ice, shoals, islands.
Kilometre 387 (Mile 242)	8.5 (28)	1.3-1.6 (0.8-1.0)	Shoals off Trail River mouth.
Kilometre 403 (Mile 252)	8.5 (28)	1.0-1.3 (0.6-0.8)	Sharp bend, narrow deep channel, islands below.
Cameron Point 419 (262)	7.9 (26)	1.6-1.9 (1.0-1.2)	Shallows, islands above curve in channel.
N.Nahanni Junction 450 (281)	8.2 (27)	1.3-1.6 (0.8-1.0)	Nahanni ice, delta, and large shoal area.
Round Island 464 (290)	10.0 (33)	1.3-1.4 (0.8-0.9)	Channel split by island.
Berry Island 482 (301)	13.1 (43)	2.9-3.2 (1.8-2.0)	Main flow diverted by Berry Island.
Kilometre 544-550 (Mile 340-344)	11.6 (38)	0.6-1.6 (0.4-1.0)	Island and large shoal area.
Kilometre 595 (Mile 372)	12.5 (41)	1.0-1.3 (0.6-0.8)	Rocky shoal and effects of Ochre R. Delta downstream.

Location	Ice or Driftwood Strand Level in m (ft)	Channel Width (Water Surface) in km (miles)	Remarks on Possible Causes of Jams
Kilometre 643 (Mile 402)	11.3 (37)	0.5-0.8 (0.3-0.5)	Narrow channel, shoals and rocks.
Fort Norman 800-814 (500-512)	12.8 (42)	1.3-3.2 (0.8-2.0)	Great Bear Rock, Windy Island, Great Bear River ice and shoals.
Kilometre 848 (Mile 530)	11.3 (37)	0.6-0.8 (0.4-0.5)	Narrow channel islands above and below.
Kilometre 928 (Mile 580)	10.7 (35)	1.3-1.6 (0.8-1.0)	Channel constricted by shoals.
Kilometre 960 (Mile 600)	12.2 (40)	1.3-1.4 (0.8-0.9)	Narrowing channel
Kilometre 976 (Mile 610)	12.2 (40)	0.8-1.6 (0.5-1.0)	Narrow channel, shoals on left bank.
The Ramparts 1078 (674)	14.0 (46)	0.3-0.5 (0.2-0.3)	Rapid channel closure.
Kilometre 1176 (Mile 735)	12.2 (40)	0.6-2.1 (0.4-0.6)	Narrow with shoals, islands above and below.
Kilometre 1267-1360 (Mile 792-850)	10.1-14.3 (33-47)	1.0-2.1 (0.6-1.3)	Shoal strewn, large bends.
Lower Ramparts 1427 (890)	10.1 (33)	1.0-1.3 (0.6-0.8)	Shoals, steep-banked narrow channel, fast-moving waters.

Technical Report
on
AERIAL RECONNAISSANCE AND STUDY RECOMMENDATIONS FOR RIVERS IN THE MACKENZIE BASIN, N.W.T.

by

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Technical Report 9 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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FOREWORD

This report is in fulfilment of a contract (408-1-0527) between Hydrologic Sciences Division, Inland Waters Branch, Environment Canada, and the Research Council of Alberta, dated 23 August 1971. The terms of the contract were to make the author available as a consultant on river studies, in connection with the Mackenzie Pipeline Evaluation Study. The report is based essentially on a three-day aerial inspection of the greater part of the Mackenzie River and the lower parts of its main tributaries.

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Thanks are expressed to Dr. O. H. Løken and Mr. D. K. MacKay of Hydrologic Sciences for arranging air transport and accommodation, and to Mr. MacKay for personal assistance and information supplied in Ottawa and Inuvik; also to Mr. R. D. May and staff of Water Survey of Canada, Calgary, and to Mr. J. P. Livingston and staff of the Department of Public Works in Edmonton, for information on the programs of their departments.

Mr. E. C. McRoberts participated in the reconnaissance and contributed to the report as part of a study on landslides along the Mackenzie River being undertaken by the Department of Civil Engineering, University of Alberta, under the supervision of Dr. N. R. Morgenstern.

INTRODUCTION

Guidelines for this study, as obtained verbally from Hydrologic Sciences Division, were approximately as follows:

(i) to look at a number of rivers, including potential crossing sites, and identify major areas of potential trouble; and

(ii) to recommend the most significant studies that should be undertaken on the physical characteristics of the major streams in the Mackenzie basin.

The rest of the report consists of two main parts. Part 2 consists of notes on the general character of various stretches of river as viewed from the air during a three-day reconnaissance. These notes are of an impressionist nature and some of the comments are essentially speculative. They are illustrated by selected prints from a set of approximately 60 black-and-white and 60 colour photographs taken by the author. Brief comments are made on some practical implications of the observations, from the point of view of constructing river crossings for pipelines or roads. Part 3 consists of brief recommendations for a long-term program of studies on the hydraulic and geomorphic characteristics of the rivers, to document information that will be of value, not only for judging pipeline proposals, but also in connection with other projects and problems that will undoubtedly come forward in the Mackenzie basin as settlement of the area continues. This program may be looked upon as a logical extension of the continuing streamflow and sediment survey program conducted by the Water Survey of Canada.

NOTES ON GENERAL CHARACTER OF RIVERS INSPECTED

2.1 Sequence of flights

These notes are based on a series of three flights on 25-27 August 1971, starting at Inuvik and finishing at Hay River. The sequence of flights and the routes followed (Fig. 1) were as follows:

Flight 1

25 August. Cessna 185 floatplane. Passengers: C. R. Neill (RCA)
David Sellars (IWB)

Inuvik to mouth of Arctic Red River.
Up Arctic Red River to 1000-ft contour (65° 45' N.), with stop at Martin House gauging station.
Due west to Snake River.
Down Snake River to Peel River.
Down Peel River to mouth, with stop at Fort McPherson.
Mouth of Peel River to Inuvik.

Flight 2

26 August. Cessna 206 floatplane. Passengers: C. R. Neill
E. C. McRoberts (U of A)

Inuvik to Mackenzie River upstream of Thunder River.
Up Mackenzie past The Ramparts to Sans Sault Rapids.
Up Mountain River to Virgin Creek (Carcajou Range).
Northeast from Mountain River to Carcajou River near Imperial River, then direct to Norman Wells.

Flight 3

27 August. Cessna 206 wheelplane. Passengers: Neill and McRoberts.

Norman Wells to Fort Norman along Mackenzie River.
Up Great Bear River to near St. Charles Creek.
Southwest to Mackenzie River at Police Island.
Up Mackenzie River to mouth of Keele River.
Up Keele River to Tertiary Creek.
Southeast from Tertiary Creek to Redstone River.
10 miles down Redstone River, then east to Mackenzie River.
Up Mackenzie River to stop at Wrigley.
Up Wrigley River and through gap to Root River at junction of Chief River.
Down Root River for 20 miles, then east across Mackenzie River to Willowlake River.
Up Willowlake River for 10 miles.
West-southwest across Mackenzie River, then down final 10 miles of Root River.
Up Mackenzie River to Camsell Bend, then west to North Nahanni River.

Down North Nahanni River to Mackenzie River.
Up Mackenzie River to stop at Fort Simpson.
Up Liard River to Birch River confluence, then east to Mackenzie River.
Up Mackenzie River to Beaver Lake, then direct to Hay River.

Weather during the flights was generally clear. Most of the inspection was done from altitudes of 1,000 to 2,000 feet. Immediately prior to the flights there had been several days of rainy weather in the lower part of the Mackenzie basin, which no doubt accounted for the noted muddy state of the Peel and Arctic Red Rivers.

Reference should be made to 1/500,000 or 1/250,000 National Topographic maps for locations mentioned in these notes.

2.2 Notes on Flight 1

Arctic Red River (travelling upstream)

(i) From the mouth to junction of Sainville River.

The river is generally well entrenched into generally flat land (Photo 1), with high banks sloping at approximately 1 vertical to 1-1/2 horizontal, but there are fragmentary terraces and small areas of floodplain. There is no great evidence of active bank erosion, most high banks being well wooded. The vegetation succession on point bars and islands indicates, however, that the river is not entirely inactive, and some eroding cliffs are visible. The water was very muddy, and point bars near the mouth appeared silty.

At Martin House (Photo 2) the water level was 12 to 14 ft below apparent bankfull stage. The 1970 record flood mark on the gauge house (located on a sandstone outcrop on the left bank) was approximately 10 ft above bankfull stage. Overbank areas are heavily wooded and probably carry very little flow. Fresh silt deposits 1 to 2 ft thick were evident at 8 ft above water level. River velocity was 2 to 3 ft/sec, and water was very muddy, probably containing several thousand p.p.m. of silt.

(ii) From Sainville River junction to Cranswick River junction.

The river changes character upstream of the Sainville River (Photo 3), probably indicating a break in slope and in geological environment. There is in general much more geomorphic activity, with erosion of high steep slumping banks (Photo 4) and formation of mid-channel islands. Flattened areas of trees are evident on many areas of the flood-plain, apparently resulting from the extreme flood of July 1970 (Photo 5). Above the Sainville River exposed sand begins to appear on channel bars. 15 miles above the Sainville, where the valley becomes noticeably deeper, gravel appears on the bars; possibly there is another break in slope at this point. Upstream of this point the channel pattern can be described as confined meanders between high valley walls, with scrolls on the flood-plain indicating active down-valley migration of the meander pattern. The Cranswick River (Photo 6) appears to supply considerable quantities of gravel bed-load to the Arctic Red, and is actively eroding some of its high valley walls.

(iii) From Cranswick River junction to 65° 45' N.

The valley slopes appear somewhat more stable, but the river takes on a more or less braided pattern, with large areas of exposed gravel bars, and much evidence of recent flattening of quite heavy tree growth (Photo 7).

The Arctic Red River was not viewed upstream of 65° 45' N.

Snake River near 66° N, 133° W.

This is a moderately-braided gravel river with high valley walls (apparently of sandstone and shale), and fairly extensive heavily-wooded flood-plain areas (Photo 8). Some of the valley walls are eroding actively. The river was quite muddy although at a low stage.

The country between the Arctic Red and the Snake Rivers near 66° N. is a dissected plateau with deep U-shaped valleys and under-fit streams.

Peel River (travelling downstream)

(i) From Snake River junction to Trail River junction at 66° 40' N.

Near the Snake River junction the Peel River has a braided channel between high steep actively-eroding valley walls (apparently of bedrock). There are extensive gravel bars and wooded islands (Photo 9). The islands and other flood-plain areas appeared to be quite low in relation to observed water level.

A phenomenon that was noted near the junction of the Snake and Peel Rivers was a small area of burning material in the middle of a high slumping bank. It appears likely that this was a burning coal seam. Camsell (1906) described similar phenomena along the Peel, and noted that large landslides occurred where burning out of lignite seams had undermined the overlying glacial drift.

Downstream of 66° 30' N. the channel becomes more well-defined, but is still irregular in pattern: it might be termed 'wandering' rather than braided (Photo 10). Sand and silt begin to appear on the exposed bars, but well-wooded islands are more prominent than exposed bars. Some tributary gullies have very steep longitudinal slopes.

(ii) From Trail River junction to Mackenzie Delta.

The channel becomes gradually more regular and well-defined, and splitting around islands becomes less common. The valley becomes shallower, and flood-plain areas appear more extensive: the latter contain numerous lakes (Photo 11). Near Fort McPherson there is some evidence of bank erosion on both sides, and the channel seems to have shifted somewhat in recent years.

Near the mouth there are well-developed meander bends and a broad wooded flood-plain with lakes, merging into the Delta (Photo 12). The river appeared quite muddy although at fairly low stage.

Fluvio-morphological features of the lower Peel River are well described by Henoch (1960), who also quotes values for the river's average slope over various stretches, based on unpublished altimeter survey data.

2.3 Some practical implications of observations on Flight 1

The Arctic Red River is probably a very significant supplier of fine sediment to the Mackenzie Delta, and should be monitored for sediment load at Martin House, at least for a period of several years. Similar considerations apply to the Peel River, which should be monitored near Fort McPherson. It is understood from Water Survey of Canada that sediment stations will be installed at these points in the near future.

On the Arctic Red River below the Sainville River junction (66° 30' N.), underground pipeline crossings would appear to pose few river engineering problems. The river does not appear to shift its channel location at any appreciable rate, and it appears at first sight unlikely that the bed is subject to appreciable depths of scour and fill, unless it is found to be underlain by some depth of sand. In the case of bridge crossings the main problems would probably be associated with ice and floating logs. There are, however, probably a few locations that should be avoided because of bank stability problems.

Upstream of the Sainville River any type of crossing on the Arctic Red River would appear to pose considerable engineering problems associated with bank stability channel shifting, and probably bed scour since there is likely to be considerable depth of alluvium at many places. In view of the notable rate at which the landscape is being eroded by natural phenomena, it appears unlikely that pipeline or road construction would add significantly to the river's sediment load (except locally and temporarily), provided that reasonable precautions were taken to minimize environmental damage. It would certainly be difficult if not impossible to detect any increase by means of a measurement program.

On the Peel River, crossings near the mouth might pose problems of scour and channel shifting in deep fine-grained alluvium. Between Fort McPherson and the Trail River junction, underground pipeline crossings would not appear to pose serious problems in general. Upstream of the Trail River junction, channel shifting, bank stability and scour require careful investigation, but it should be possible to find some relatively good crossing sites.

2.4 Notes on Flight 2

Mackenzie River between Arctic Red River and Norman Wells (travelling upstream)

The Mackenzie River was not given detailed attention over most of its length, since it was assumed that a considerable amount of information on its characteristics and behaviour is available from federal agencies. These notes are therefore fairly superficial.

Between Arctic Red River and The Ramparts large sand bars were noted in mid-channel (Photo 13). Well-developed dune forms on the bars (Photo 14) indicated recent active sand transport. The banks, believed to consist mainly of limestone, appeared generally stable, but minor erosion was apparent on the

outsides of bends. No landslides of any magnitude were observed.

In the vicinity of The Grand View (66° 50' N.), silt-sand deposits were noted on the banks, and there were many exposed sand-bars. The river water appeared quite clean compared to the Arctic Red and Peel Rivers.

The Ramparts is quite a remarkable phenonemon of river morphology, whose origin is presumably associated with the glacial epoch (Photos 15 and 16). Extensive rock outcrops were evident in the river bed above the entrance to the gorge.

Rock dredging activity was noted at the Sans Sault Rapids just below the mouth of the Mountain River.

The stretch between Sans Sault Rapids and Norman Wells was not viewed from the air, but has been inspected on aerial photographs. Bank instability appears to be restricted to shallow earth-falls and minor earth-flows, with the single exception of a large rotational slide on the right bank opposite the northeast corner of Axel Island (RCAF Photo A 19947-44).

Mountain River between its mouth and Carcajou Range (Virgin Creek) (travelling upstream)

The Mountain River is probably an important supplier of coarse bed-load to the Mackenzie River: it is significant that the Mackenzie channel becomes wider and exhibits more splitting around bars and islands for some distance downstream of the Mountain River mouth. It is likely that an accurate slope profile would also show an increase in the slope of the Mackenzie in this area.

Over the length viewed the Mountain River is generally a wide highly-braided gravel-bed stream of steep longitudinal slope, exhibiting large areas of exposed sand-and-gravel bars (Photo 17). Trees on bars and islands were extensively flattened by the record flood of July 1970 (Photo 18).

For a distance of some 10 miles above the mouth, numerous large-scale landslides are evident along the right or south bank, in what appear to be unconsolidated materials (Photos 19 and 20). At 12 to 14 miles above the mouth, steeper more stable cliffs, apparently consisting of shales, are seen on the right bank.

Near the junction of the Gayna River (65° 25' N.) the Mountain River is entrenched in a deep bedrock gorge with highly-folded strata (Photo 21). A few miles upstream of this junction it is again highly braided (Photo 17). The Gayna River is also highly braided. At its emergence from the mountains the Mountain River displays a typical alluvial fan (Photo 22).

Carcajou River near junction of Imperial River

The river exhibits a pattern of confined meanders in a deep narrow valley, with well-wooded slopes and flood-plain (Photo 23). The meanders probably migrate appreciably down-valley, but the valley walls appear generally stable. The bed-material appears to be gravel.

2.5 Some practical implications of observations on Flight 2

The Mackenzie River between Arctic Red River and Norman Wells does not appear to pose any special problems in planning pipeline crossings, apart from those normally investigated for any large river crossing. Investigation of the depth of sand present is of prime importance, since it is evidently highly active and subject to scour at high flows. In the case of bridge crossings, ice conditions during break-up would be an important matter for detailed investigations, according to all accounts. Bank instability does not appear to be a serious problem in most of the length under discussion, at least under present natural conditions.

With reference to contemplated measurements of ice pressures during break-up at the entrance to the Ramparts, in the writer's opinion it would be wise to undertake one or two seasons' observation of the phenomena before attempting to design and install force-measuring devices. Observations should include aerial and ground viewing, movie and time-lapse photography, and recording of water-level changes. At a site of this scale it might be fruitless to decide on the type and location of force-measuring devices without sufficient documentation of what actually happens.

The Mountain River seems to pose considerable problems for underground pipeline crossing: unstable banks, particularly in the lower reaches; a wide shifting channel; and possibly considerable depths of alluvium subject to scour during floods. In the case of bridge crossings channel training works would be advisable to permit an economical length of bridge. The gorge below the Gayna River junction seems to be the only practicable location for hydrometric gauging, and might also be used for sediment transport measurements including bed-load.

In the case of the Carcajou River at the location viewed (Photo 23), the main problems requiring investigation would be shifting of the main channel and possible scour in the alluvial valley fill.

2.6 Notes on Flight 3

Mackenzie River between Norman Wells and head of river (travelling upstream)

(i) Norman Wells to Wrigley.

In the vicinity of Norman Wells sandstone outcrops occur along the right bank, and the banks are generally stable and well-vegetated with gravel and cobble beaches below, the latter apparently formed by wave action. Significant erosion appears to be generally confined to the banks of islands. Extensive sand bars and islands were noted.

Some earth falls were noted at Ten-Mile Island and in the vicinity of Halfway Island. Approximately two miles downstream of Great Bear River

there is a large semi-circular landslide apparently associated with melting of frozen ground (Photo 24).

Clear water inflowing from the Great Bear River was visible as a distinct flow along the Mackenzie right bank for several miles, indicating only slow lateral diffusion in the river.

Between Police Island and the Keele River there are several areas of sliding banks (Photos 25 and 26), as well as extensive channel splitting around sand bars and wooded islands (Photo 27). The primary cause of instability in this area seems likely to be inflow of coarse bed-load from the Keele and Redstone Rivers. Slides appear to occur only on the high right bank.

Between the Redstone River junction and Wrigley, the Mackenzie generally flows in a single channel of fairly regular width, with little sign of lateral shifting or bank instability (Photo 28), except at the right-angle bend below the Blackwater River. There is a clear-cut 'trim line' on each bank, with heavy timber above it and cobbled beaches below it of about 1 in 2 slope. This trim line may correspond approximately to average annual flood level.

(ii) Wrigley to Camsell Bend

This stretch was viewed at only a few points. Between McGern Island and Camsell Bend the channel is wide and extensively split around islands (Photo 29); this probably results from inflow of coarse bed-load supplied by the Root and North Nahanni Rivers. Inspection of aerial photographs indicates generally stable banks, with occasional shallow earth-flows and some larger-scale instability in the vicinity of McGern Island.

(iii) Camsell Bed to Fort Simpson.

Many large-scale landslides were observed on this stretch. Some appear to be recent and presently active (Photo 31), while others appear to be older and more stabilized (Photo 32). The slide mass shown in Photo 32 (see also 1961 RCAF Photo A 17504-31) is some 11,000 ft long and 2,000 ft wide, and does not appear to be as active now as it was in 1961. The slide shown in Photo 31 appears in the distance in Photo 32, but is not evident in the 1961 airphotos. Both of these slides appear to be of somewhat unusual shape: they may be associated with some type of frozen ground phenomenon.

(iv) Fort Simpson to head of river.

Bank heights are low in this stretch and no bank instability or erosion was observed. Sand dunes were clearly visible on bars both above and below water. Boulders in the river suggest the presence of till in the banks.

Great Bear River between the mouth and St. Charles Creek

The Great Bear is a stable river with a well-defined single channel. Its gravel bottom was clearly visible through several feet of clear water. Between the mouth and the junction of the Brackett River (Photo 30) some bank slides were noted in poorly-consolidated Tertiary deposits (Hume, 1923).

Farther upstream the banks were well wooded and generally stable, except for shallow surface slides in areas burned over by forest fires.

Keele River between the mouth and Tertiary Creek

The Keele (Photo 33) is a braided gravel river with shifting channels, generally not entrenched into the terrain to a noticeable degree. Between 5 and 10 miles above the mouth, however, there are high slumping banks of grey material on the left side.

Redstone River from 64° 00' to 64° 05' N.

The Redstone (Photo 34) is quite similar to the Keele in character, but appears to be more deeply entrenched into the terrain. Some high slumping banks at the valley wall were noted. Although viewed at a low stage of flow, the water appeared muddy and fast-flowing.

Dahadinni and Johnson Rivers near their mouths (Mackenzie left bank)

Both these rivers (Photos 35 and 36) are well entrenched into the terrain a short distance above their mouths, and appear to have stable well-wooded banks and fairly well-defined channels. Both supply coarse bed-load to the Mackenzie.

Blackwater and Ochre Rivers near their mouths (Mackenzie right bank)

Both these rivers (Photos 37 and 38) pass through gaps in the McConnell Range and are generally well entrenched between the range and the Mackenzie River. The Blackwater has some areas of heavily-wooded flood-plain near the mouth. Sandy alluvial fans occur at the mouths. No evidence of bank instability was noted.

Wrigley and Root Rivers below Mackenzie Mountains (Mackenzie left bank)

The Wrigley River (Photo 39) is a meandering stream in a fairly wide valley, with a heavily-wooded flood-plain and generally stable banks except for some erosion where it impinges on the valley walls.

The Root River is quite variable in character. At the junction of Chief River, where it emerges from the Mackenzie Mountains, it is a highly braided gravel-bed stream with shifting channels (Photo 40). Farther downstream in the trench east of Camsell Range its channel width greatly diminishes and its pattern changes to confined meanders in a wide valley. Near the mouth it exhibits extensive sand bars.

Willowlake River, last 10 miles

The Willowlake River (Photo 41) is of similar character to the Blackwater and Ochre Rivers, and exhibits a fairly stable meander pattern in a valley of moderate width. Near the mouth there is a heavily wooded flood-plain. Bank instability is generally limited to minor erosion where meander bends impinge on the valley walls. The river bed appears to be sandy. There is a well-defined trim line along the banks, probably corresponding to average annual flood level.

North Nahanni River below Mackenzie Mountains

The North Nahanni below its emergence from the main mass of the Mackenzie Mountains at 124° 00' W. is mainly a braided gravel-bed stream (Photos 42, 43, 44). It appears to have moderate slope and velocity, but is subject to considerable channel shifting in a broad alluvial valley between outlying ranges of the Franklin and Mackenzie Mountains. We have not investigated the geomorphic history of this area, but it is obviously complex: it appears likely at first sight that there is a considerable depth of alluvial fill in the 20-mile stretch above the mouth. The North Nahanni probably supplies a considerable quantity of coarse sediment to the Mackenzie River.

Liard River between junction of Birch River and the mouth

The Liard presents the impression of a stable river entrenched into resistant materials (Photo 45). Banks are high, slope at nearly 1:1, and are generally well-wooded except where slow erosion is occurring on the outsides of bends. There is no flood-plain and no channel bars were noted, but riffles and rapids at various points suggest the presence of rock outcrops in the bed. The channel width is in general remarkably regular. No signs of recent high flooding were seen. The channel pattern might be described as irregularly sinuous, rather like the Mackenzie in its single-channel reaches.

One large landslide was noted on the outside of a right-angle bend at 61° 26' N. (Photo 46). Another slide was seen on the left bank below the junction of the Poplar River.

2.7. Some practical implications of observations on Flight 3

Several stretches of the Mackenzie River upstream of Norman Wells appear to pose considerable bank stability problems not only for pipeline crossings but also for routes parallel to the river, since ground for some distance back from the river appears subject to large-scale shallow slides. The more susceptible stretches appear to be as follows:

Around Ten-Mile and Halfway Islands.

From upstream of Police Island to Keele and Redstone Rivers.

Around McGern Island (Willowlake River).

Camsell Bend to Martin River.

The left bank tributaries Keele, Redstone and North Nahanni appear to be important suppliers of coarse sediment (and probably also of fine sediment) to the Mackenzie River. If any attempt is to be made to determine a sediment balance for the Mackenzie, it is important that these streams should be monitored for sediment load, despite the obvious difficulties in finding suitable gauging sites. With reference to pipeline and road crossings these streams present similar problems to the Mountain River, as previously discussed: wide floodways with shifting channels, unstable banks, and probably considerable thickness of alluvial deposits subject to scour in floods. The other tributaries with the possible exception of the Root, seem to be relatively inactive

geomorphologically and would not appear to pose serious crossing problems from a river engineering point of view.

Various more or less distinct types of landslides were observed along river banks, but no attempt will be made to categorize them on the basis of a superficial reconnaissance. The most disturbing from a practical point of view are unexplained large-scale slides that occur as isolated phenomena in otherwise stable well-vegetated banks (Photos 24, 31, 46), and which may be associated with some disturbance of thermal regime. Shallow earthflows associated with recent forest fires were noted in many areas. It therefore appears likely that at many stream crossings bank instability resulting from disturbance of the vegetation might be as important a matter for concern as erosion and scour by the stream. Of particular concern is the type of large-scale mass movement seen on Photo 32, which can affect an area extending far back from the river-bank.

PRELIMINARY RECOMMENDATIONS FOR PROGRAM OF FLUVIOLOGICAL STUDIES

3.1 Scope

It is assumed that the role of the federal government in pipeline projects will be to provide certain basic information and to judge proposals according to environmental standards, and that local engineering studies for river crossings would be commissioned by the promoters. These recommendations are therefore not directed specifically to pipeline crossings or to particular sites. They are concerned with initiating a continuing program of investigations into the physical properties of the rivers in the Mackenzie basin, and to publishing appropriate reports containing basic information. The recommendations are based primarily on the author's experience within the Alberta Cooperative Research Program in Highway and River Engineering*, and on the example of a comprehensive report on river investigations in West Africa. (See Neill 1964, Neill and Galay 1967, Neill and others 1970, Kellerhals and others 1972, and NEDECO 1959.)

No attempt is made to set out schedules or costs, since it is considered that this is a matter for later consideration after these recommendations have been examined by all interested parties.

3.2 Basic geographical information

Maps and airphotos. It appears that basic topographic and geologic mapping is well under way and that extensive airphoto coverage is available. 1/50,000 topographic maps are valuable for river studies.

River profiles. The only longitudinal profile that appears to be available is a very small-scale one of the Peace-Mackenzie system, contained in the Atlas of Canada. Reasonably accurate slope profiles should be prepared for the Mackenzie and all major tributaries. How to do this economically is a matter for consultation among the various federal agencies that have survey information and facilities. The following scales might be considered for final presentation:

Mackenzie and low-gradient tributaries:	1" = 20 miles horizontally
	1' = 50 feet vertically
High-gradient tributaries up to 2,000' contour:	1" = 10 miles horizontally
	1' = 200 feet vertically

* Participating agencies: Research Council of Alberta.
Dept. of Civil Engineering, University of Alberta.
Dept. of Highways and Transport, Alberta.
Water Resources Division, Alberta Dept. of the Environment.

or approximate metric equivalents. Original plotting scales might be two or more times larger. Quoted elevations should refer to water surface at a consistent discharge (mean annual flow suggested). It is desirable that quoted elevations be accurate to *within a foot* or less on flat-slope streams; on the higher reaches of the mountain rivers, however, such accuracy is probably not warranted. The average slope of the Mackenzie appears to be approximately *0.6* ft per mile.

Figure 2 shows a sample of an Alberta river profile as prepared in preliminary form for a forthcoming publication.

Drainage area/length relationships. Graphs should be plotted for each major stream showing drainage area against length from mouth. The curves will be stepped at principal tributary junctions, and may be estimated between junctions. Such graphs are valuable for interpolating and extending hydrologic data.

Division of rivers into more or less homogeneous stretches. An attempt should be made to separate each river into a series of more or less homogeneous stretches, and to show the divisions on a map of the basin. Some such division is already indicated in Part 1 of this report: for example, the Arctic Red River is broken for descriptive purposes into three stretches which on first sight appeared to have markedly different characteristics. The division should take into account breaks in slope, notable changes in channel pattern, junctions of principal tributaries, and geological boundaries. In the case of the Mackenzie, the following division appears natural:

1. Fort Providence to 120° W.
2. 120° W. to Liard River.
3. Liard River to North Nahanni River.
4. North Nahanni River to Wrigley.
5. Wrigley to Redstone River.
6. Redstone River to Fort Norman.
7. Fort Norman to Sans Sault Rapids.
8. Sans Sault Rapids to Fort Good Hope.
9. Fort Good Hope to Arctic Red River.
10. Arctic Red River to Point Separation.

Subsequent description and collection and tabulation of information can then be arranged in similar fashion, so that data on channel dimensions and other properties indicate mean values and other statistical measures for each more or less homogeneous stretch. This is more informative than simply quoting measured values at a particular station.

Photography. Water Survey staff and other federal personnel travelling on or flying over the rivers should be encouraged to take aerial oblique and ground photographs and slides illustrating significant geomorphic features, flow conditions, ice phenomena, etc. Photographs selected for their illustrative and pictorial qualities should be filed systematically, and should be available for public inspection in Ottawa, Inuvik and perhaps other centres. Maps indicating the location and orientation of photographs should accompany the collections. Dates and times of all photographs should be recorded so that they can be correlated with measured flows. Motion pictures of floods and ice break-up would be particularly valuable.

3.3 Water, sediment and ice survey

This section deals with the data traditionally collected by the Water Survey: discharges, stages, sediment loads and ice data. Water Survey of Canada Calgary district office has supplied a list of existing and proposed water and sediment gauging sites in the Mackenzie Basin. Some comments on this program appear to be called for.

Discharge data. In 1971-72 the Mackenzie was gauged at three sites: Providence, Fort Simpson and Norman Wells. A fourth station near Arctic Red River is on the program for 1972-73. This coverage appears to be quite adequate.

In 1971-72 gauging stations were operated on eight tributaries: Kakisa, Trout, Liard (plus South Nahanni), Willowlake, Redstone, Great Bear, Arctic Red, and Peel; of which the Redstone gauge is slated for abandonment because of operational difficulties. The following major tributaries have not been gauged: North Nahanni, Root, Dahadinni, Blackwater, Keele, Carcajou, Mountain, Hare Indian, Ramparts.

A list of seventeen tributaries has been proposed for installation of gauges in 1972-73, but WSC indicate that not more than six of these will actually be installed. This additional list does not include the North Nahanni, Root and Dahadinni Rivers.

In selecting gauging stations, WSC naturally lays considerable stress on practicability of installation and operation and on the probability of obtaining reliable records. One wonders, however, whether criteria for station selection that may be valid in more densely gauged regions are reasonable in the Mackenzie basin; also whether too much reliance is placed on conventional gauging by rated cross-sections. It might be worthwhile considering lower-standard gauges at a number of sites which would be operated intermittently or for a limited period of years only. The feasibility of intermittent discharge measurements by means of tracers might also be considered for the more difficult tributaries such as the Keele River.

At this point it may be appropriate to comment on WSC data publications. It has always seemed to the writer that the traditional hydrometric yearbooks are too exclusively concerned with daily discharge tabulations and give insufficient assistance to users wishing to estimate absent data. If graphical hydrograph correlations were shown between stations in the same

region, it would often be possible to sketch hydrographs for stations with intermittent data. Cross-referencing or summarizing of meteorological information on significant run-off events might be included. Hydrologic yearbooks from certain other countries (e.g. New Zealand's "Hydrology Annual" include extensive graphical presentations, storm maps, photographs and other data which give the user a much better feel for the information than do stark tabulations of figures. Another result of preoccupation with daily discharges is that the often-useful stage data are downgraded: stages are not published, and gauges are often shifted short distances for reasons of operational convenience, thereby breaking the continuity of the stage record. It would seem particularly important to document flood events year by year in the NWT, where the scarcity of human settlements means that information cannot be collected years later by means of interviews and searches.

Stage data. In addition to the three discharge stations mentioned above, in 1972-73 there will be eight stations on the Mackenzie River recording stages only. Accurate geodetic elevations should be established at all these sites.

Consideration should be given to installing stage recorders at a few sites on all the major tributaries, even where reliable discharge measurements are not considered feasible. These records might prove extremely useful at a later date for various purposes, including discharge estimation. The cost of a simple stage record should be much less than that of a daily discharge record.

Sediment data. In 1971-72 sediment was measured only at Fort Simpson on the Mackenzie, and on none of the tributaries. For 1972-73, sediment measurements are planned at four sites on the Mackenzie and on four major tributaries: Liard, Willowlake, Arctic Red, and Peel. It is notable that this list does not include any of the braided left-bank tributaries which appear to supply considerable quantities of sediment, particularly coarse load.

From the viewpoint of establishing some kind of sediment balance for the basin, it would seem necessary to measure suspended loads in at least two of the following streams, at least on an intermittent or limited-period basis: North Nahanni, Root, Redstone, Keele, Mountain, Ramparts. The justification for two stations on the Mackenzie upstream of the Liard (plus one on the Liard near its mouth) is not clear, because from geomorphic considerations little sediment supply would be expected in this stretch.

Special consideration should be given to immediate sediment monitoring on clearer streams that might be adversely affected by pipeline crossings and by construction practices liable to cause deterioration of their watersheds.

Efforts should be made to measure bed-load by one means or another on the Mackenzie, Redstone, Keele, Mountain and Peel Rivers. If damming of any of these rivers is contemplated, the downstream effects of interrupting the sediment transport would require careful consideration.

Ice data. It is assumed that ice thickness, ice season dates, and water temperatures will be recorded systematically and published for all hydrometric stations operated by the Water Survey. Every opportunity should be taken of recording ice thicknesses at other points on the rivers-particularly

late winter thicknesses. The thickness of ice liable to contact structures during break-up is an important factor in the design of river structures.

It may be appropriate to consider publishing ice thicknesses and water temperatures in the hydrometric yearbooks, rather than separately. It is interesting to note that recently issued Water Survey summaries of these data have used graphical presentations, rather than the strictly tabular form used for discharge data.

Attention should be given to dates of freeze-up and break-up as well as to dates of first and last ice. For engineering purposes the former are often more significant.

3.4 Hydraulic geometry

Channel cross-sections. Sufficient river cross-sections should be surveyed to establish mean values and ranges of channel dimensions within each of the "more or less homogeneous stretches" discussed previously (Section 3.2). The number required will depend on how finely the division into stretches is done, and on how regular the river appears, but probably at least 10 cross-sections should be surveyed in each stretch. Measured cross-sections should extend right across the flood-plain (if present) and up to expected extreme flood level. The nature of vegetation on flood-plain areas and islands should be described and recorded photographically, with particular attention to its effects on flow over the flood-plain. Cross-sections should be referenced initially to water-level at time of survey, then adjusted to a common datum corresponding to a consistent discharge along the river.

The proposed 10 or more sections to be surveyed in each stretch of river might be spread out over the stretch, or concentrated into one or more relatively short reaches, depending on the homogeneity of the stretch, and on accessibility and other practical factors.

As touched on previously in the sub-section "Stage data" of Section 3.3, it would be useful to obtain some kind of stage record at at least one point in each river stretch. This need not be a continuous record, provided stages are obtained over a good range of flows. The stages could be rated approximately as to discharge by correlation with discharge-measuring stations, or by means of occasional flow-metering. Some form of maximum-stage gauge, read at yearly intervals, might be acceptable.

Flow velocities and hydraulic roughness. In each river stretch a relatively uniform reach should be selected for determination of mean flow velocities and hydraulic roughness at various stages. This requires determination of local slope, average cross-section, and a stage-discharge relation or direct velocity observations. Surface velocities should be measured by floats under flood conditions wherever possible.

Longitudinal depth profiles. Echo-sounder depth profiles should be run along all stretches capable of navigation by a shallow-draft boat, to record the longitudinal variations in depth along the apparent thalweg. Cross-sections should be sounded at convenient intervals, particularly at constrictions, bends, cliffs and other points liable to deep scour. The

profile datum should be tied to stage observations at gauging stations or other definite points. Sounder traces should be tied to recognizable fix points using maps or airphotos.

3.5 Alluvial materials and stratigraphy

Channel bed materials. Representative bulk samples should be obtained of channel bed materials at convenient intervals, and analyzed for grain-size distribution, density, and mineralogical composition. In coarse-bed streams where bulk sampling is impracticable, surface sampling by the grid method may be used (Kellerhals and Bray, 1971). The variation of median grain-size along the stream should be shown on the slope profile.

Bank and flood-plain materials. Representative samples should be collected, and bank stratigraphy and flood-plain materials should be described at measured cross-sections. Geological stratigraphy in high eroding cliffs and banks should be recorded where practicable.

Sub-bed materials. From the point of view of estimating possible scour, the sub-bed stratigraphy is of prime significance. Efforts should be made to collect any available data from engineering, seismic, or other borings in channels and flood-plains. Geological and geomorphic studies may indicate the probable nature of the sub-bed materials in many cases. In deeper rivers, such as the Mackenzie and Lower Peel, seismic profiling from boats give useful indications of depths of alluvium overlying consolidated materials. Available information should be shown on slope profiles. In view of the expense of wet drilling, it should probably not be considered as part of a general study program, but should rather be confined to specific sites of engineering projects. Seismic refraction techniques may be applicable in some cases.

Special attention should be given to the location of permafrost and ice beneath river beds.

3.6 Channel processes and special studies

Channel shifting. Airphotos of selected stretches taken at intervals of time should give a good record of channel shifting if sufficient ground control is recognizable on the photographs. It may be worthwhile laying out lines of erosion stakes at selected locations. For many of the flat-slope tributaries the rates are likely to be negligible, but on the steep left-bank tributaries they are likely to be high in many places. In the Mackenzie River comparison of navigation charts of various dates may yield valuable information.

Bed forms and movement. Efforts should be made to track and record the shifting of major bars on selected reaches of the Mackenzie and the larger tributaries, and to relate this to estimates of bed-load transport arrived at by other means such as direct sampling. The dimensions of minor bed forms under various flow conditions, as detected by echo-sounding, should be recorded as a matter of scientific interest.

Hydrophone and tracer studies should be made at selected locations concerning the stage of flow at which significant bed movement begins.

Scour. Documented information on scour depths and processes in natural streams and around structures is presently scarce (Neill, 1964). A number of locations characterized by channel constrictions, sharp bends, structures or steep cliffs should be selected and should be regularly monitored for scoured depths at various stages. These locations should be selected where the bed is likely to be subject to cyclic scour and fill. Depths in the Mackenzie Ramparts should be carefully surveyed, and an attempt made to analyze and explain the anomalous geometry of this section, as a matter of scientific interest.

Ice conditions and processes. It may be surmised that in the Mackenzie basin ice plays a more important role in the rivers' regime than in more southern regions. Systematic observations should be made of ice conditions, especially during spring break-up, with particular reference to ice erosion, jamming, and action on obstructions and any structures that may exist. Reference has already been made to proposed observations at The Ramparts in Section 2.5 of the report. Factors requiring documentation include the duration of major ice runs, the maximum thicknesses, velocities and plan dimensions of ice floes, the heights of jams and their physical structure, the temperature and strength of ice immediately preceding breakup, and observed destruction and damage to engineering installations. Installation of force-measuring devices might be considered at The Ramparts and other sites after the physical nature of the phenomena is documented.

Flood observations. Special attention should be given to observations of river behaviour under extreme flood conditions. High water level marks should be recorded along a river immediately after a major flood, and aerial photography obtained of extent of flooding and other notable phenomena at the peak of the flood, where practicable. Efforts should be made to measure maximum scoured depths at significant points during or immediately after the flood peak. These flood observations are especially important in the Mackenzie basin, where the density of regular hydrometric gauges is likely to be low for some time to come.

Coordination with landslide studies. Studies of channel processes should be coordinated closely with geotechnical studies on river-bank landslides, because of frequent interactions between fluvial erosion, landslides and channel instability.

3.7 Compilation of historical material

A search should be made of the scientific and general literature, and of unpublished records such as those of the H.B.C., for information relating to the physical characteristics and behaviour of the rivers in the basin, and of their exploration and development for human use. Information obtained should be consolidated into a historical account with bibliography. The NEDECO report (1959) on the Rivers Niger and Benue included this type of material.

Special attention should be given to any historical accounts of flood heights and ice conditions that may be found in unpublished records. Old

photographs should be collected and compiled.

3.8 Geologic and geomorphic studies

It is assumed that studies are being or will be conducted on the geological evolution of the area in the Quaternary period. The recent evolution of the present valleys and river courses is a matter of considerable interest in connection with their present regime. It may be of considerable practical assistance towards inferring the nature of materials beneath their beds and the probable effects of interfering with their natural regimes by engineering works. It is therefore desirable that a glacial geologist or geomorphologist should be closely associated with the proposed fluviological studies, and that an evaluation of the rivers' geomorphic history and present trend be included in any report or reports that are prepared.

3.9 Publication of information collected

It is important that information collected should be published as soon as possible after processing. The arrangement and format of reports cannot, however, be conveniently discussed until decisions are made on the resources to be allotted to the proposed studies and on their scheduling. Consideration might be given to early publication of a general-type report containing a broad picture of the rivers in the Mackenzie basin, to be followed by more detailed reports on individual rivers or smaller regions.

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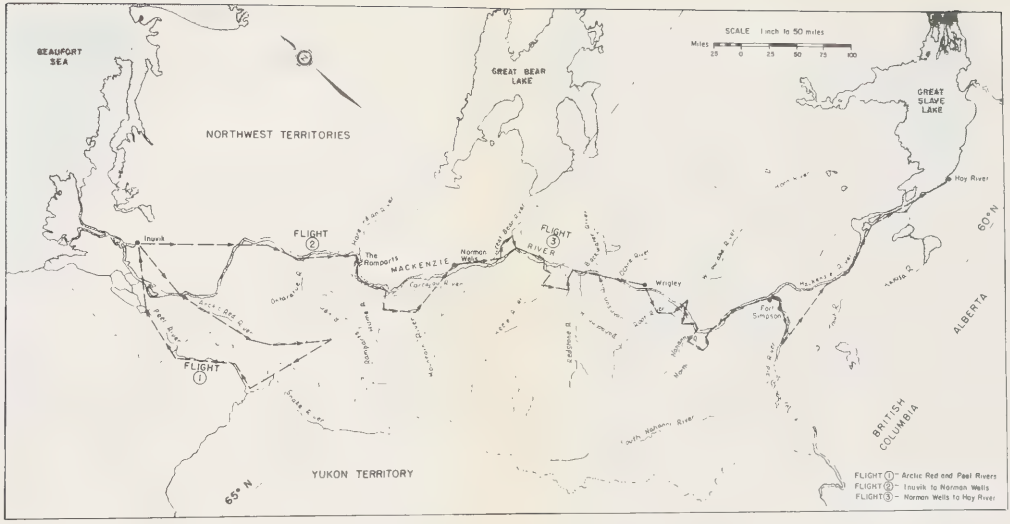


FIG 1-Map showing approximate routes of aerial inspection flights, 25 – 27 August 1971

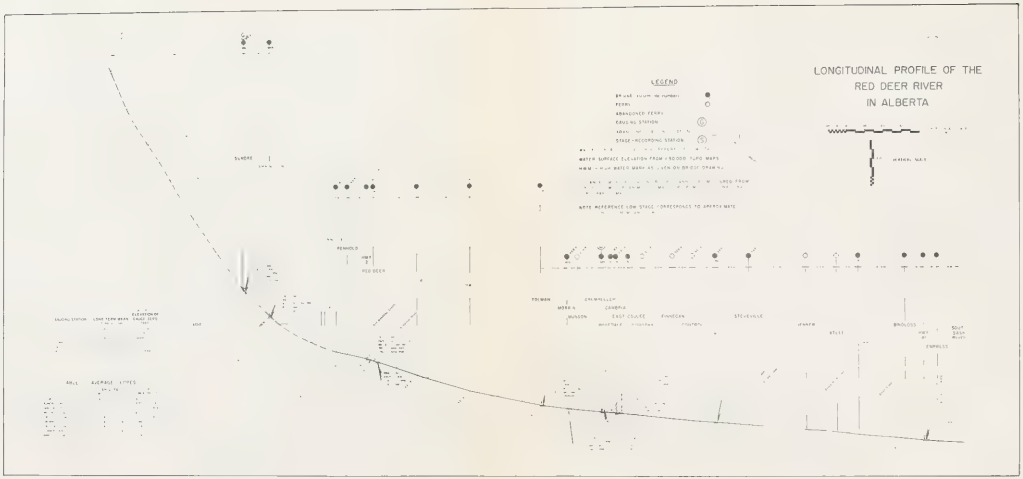


Fig 2 – Sample longitudinal profile of river in Alberta

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2. Arctic Red River at Martin House gauging station.
Note stage-recorder shelter on bank.

3. Arctic Red River approximately 10 miles upstream of Sainville River Junction.

4. Arctic Red River below Cranswick River junction.
Note high slumping bank and sand-and-gravel bars.

5. Flattened trees on Arctic Red River resulting from 1970 flood.
(Approximately 15 miles upstream of Sainville River.)

6. View down Cranswick River to junction with Arctic Red River.
Note steep slumping cliff on right bank.

7. Arctic Red River upstream of Cranswick River junction.
Note trees flattened by 1970 flood.

8. View down Snake River near 66° N, 133° W.

9. View down Peel River below Snake River junction.
(Braided channel pattern.)

10. View down Peel River in vicinity of 66° 40' N.
(Wandering channel pattern.)

11. Peel River above Fort McPherson.

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13. Mackenzie River below Thunder River junction.

14. Mackenzie River above Thunder River junction.
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15. Mouth of The Ramparts, Mackenzie River, from
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18. Mountain River: trees flattened by 1970 flood.

19. View down Mountain River to its mouth (East Mountain in background).
Numerous landslides occur along right bank.

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24. Landslide and mudflow on Mackenzie River downstream of the Great Bear River.

25 and 26. Landslides on right bank of Mackenzie River approximately 20 miles downstream of Keele River junction. Banks are in the order of 200 feet high, and are apparently composed of silty material.

27. Mackenzie River downstream of mouth of Keele River.

28. View down Mackenzie River past mouth of Dahadinni River.

29. View up Mackenzie River above McGern Island.

30. View down Great Bear River; junction of Brackett River on right.

31. Recent slide on left bank of Mackenzie River downstream of Martin River junction.

32. Old massive slide area on left bank of Mackenzie River upstream of Photo 30. Toe of slide seen in Photo 30 can be seen in the distance.

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34. View up Redstone River near 64° 00' N.

35. View up Dahadinni River near the mouth.

36. View up Johnson River from the mouth.

37. Mouth of the Blackwater River.

38. Mouth of the Ochre River.

39. View down Wrigley River towards Mackenzie River. (Mount Gaudet in middle background.)

40. View down Root River from the north end of the Camsell Range.

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43. View up North Nahanni River from 62° 10' N. Battlement Creek in lower left corner. (Note: this location is subject to some doubt.)

44. View down North Nahanni River towards the mouth from 123° 30' W: Nahanni Range on right, Lone Mountain in middle distance.

45. View up Liard River from 61° 40' N.

46. Recent slide on right bank of Liard River at 61° 26' N.



Photo. 1 - Arctic Red River opposite Swan Lake



Photo. 2 - Arctic Red River at Martin House gauging station. Note stage-recorder shelter on bank



Photo. 3 - Arctic Red River approximately 10 miles upstream of Sainville River junction.

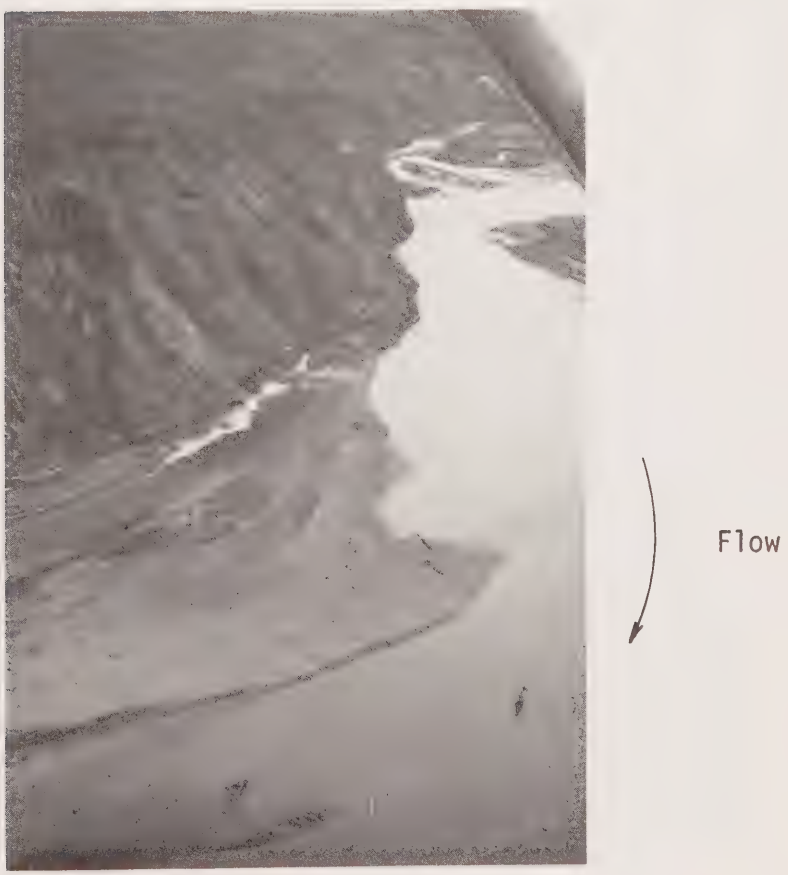


Photo. 4 - Arctic Red River below Cranswick River junction. Note high slumping bank and sand-and-gravel bars.



Photo 5 - Flattened trees on Arctic Red River resulting from 1970 flood. (Approximately 15 miles upstream of Sainville River.)



Photo 6 - View down Cranswick River to junction with Arctic Red River. Note steep slumping cliff on right bank.



Photo 7 - Arctic Red River upstream of Cranswick River junction. Note trees flattened by 1970 flood.



Photo 8 - View down Snake River near 66° N, 133° W.



Photo 9 - View down Peel River below Snake River junction. (Braided channel pattern.)



Photo 10 - View down Peel River in vicinity of 66° 40' N. (Wandering channel pattern.)



Photo 11 - Peel River above Fort McPherson.



Photo 12 - Peel River, view towards the mouth.



Photo 13 - Mackenzie River below Thunder River junction.



Photo 14 - Mackenzie River above Thunder Bay junction. Note dunes on large sand bar.



Photo 15 - Mouth of the Ramparts, Mackenzie River, from approximately 1,500 ft altitude.



Photo 16 - Mouth of The Ramparts from approximately 700 ft altitude.



Photo 17 - View down Mountain River above junction of Gayna River.



Photo 18 - Mountain River: trees flattened by 1970 flood.



Photo 19 - View down Mountain River to its mouth.(East Mountain in background). Numerous landslides occur along right bank.

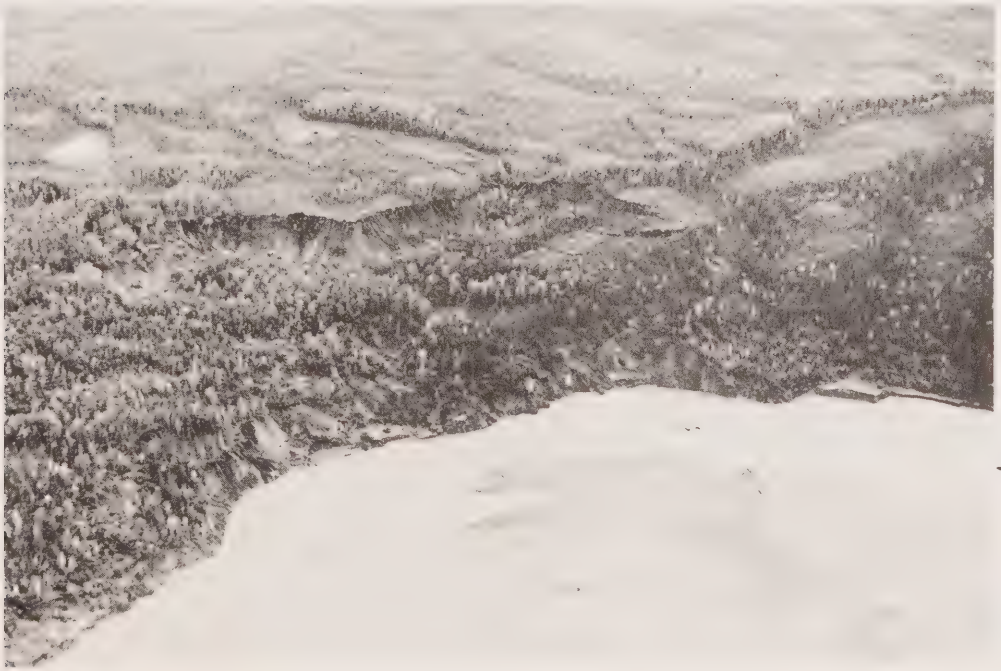


Photo 20 - Landslide on Mountain River approx imately 3 miles above the mouth.



Photo 21 - Junction of Gayna River with Mountain River.



Photo 22 - View up Mountain River at its emergence from Carcajou mountain range.



Photo 23 - View down Carcajou River below junction of Imperial River.



Photo 24 - Landslide and mudflow on Mackenzie River downstream of the Great Bear River.





Photos 25 and 26 - Landslides on right bank of Mackenzie River approximately 20 miles downstream of Keele River junction. Banks are in the order of 200 feet high, and are apparently composed of silty material.



Photo 27 - Mackenzie River downstream of mouth of Keele River.



Photo 28 - View down Mackenzie River past mouth of Dahadinni River.



Photo 29 - View up Mackenzie River above McGern Island.



Photo 30 - View down Great Bear River; junction of Brackett River on right.



Photo 31 - Recent slide on left bank of Mackenzie River downstream of Martin River junction.



Photo 32 - Old massive slide area on left bank of Mackenzie River upstream of Photo 31. Toe of slide seen in Photo 31 can be seen in the distance.



Photo 33 - View up Keele River towards junction of Tertiary Creek.



Photo 34 - View up Redstone River near 64° 00' N.



Photo 35 - View up Dahadinni River near the mouth.



Photo 36 - View up Johnson River from the mouth.



Photo 37 - Mouth of the Blackwater River.



Photo 38 - Mouth of the Ochre River.



Photo 39 - View down Wrigley River towards Mackenzie River. (Mount Gaudet in middle background).



Photo 40 - View down Root River from the north end of the Camsell Range.



Photo 41 - View up the Willowlake River from approximately 8 miles above the mouth.



Photo 42 - View up North Nahanni River from 62° 20' N.



Photo 43 - View up North Nahanni River from 62° 10' N. Battlement Creek in lower left corner. (Note: this location is subject to some doubt)



Photo 44 - View down North Nahanni River towards the mouth from 123° 30' W: Nahanni Range on right, Lone Mountain in middle distance.



Photo 45 - View up Liard River from 61° 40' N.



Photo 46 - Recent slide on right bank of Liard River at 61° 26' N.

DENDROCHRONOLOGICAL INVESTIGATIONS ALONG THE MACKENZIE, LIARD AND SOUTH NAHANNI RIVERS, N.W.T.
PART I: USING TREE DAMAGE TO DATE LANDSLIDES, ICE JAMMING AND FLOODING

by

M.L. Parker and L.A. Jozsa

Technical Report 10 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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DENDROCHRONOLOGICAL INVESTIGATIONS ALONG THE MACKENZIE, LIARD, AND SOUTH NÄHANNI RIVERS, NORTHWEST TERRITORIES

PREFACE

This report relates the dendrochronological aspects of a field trip undertaken between June 5 and July 12, 1972 along the Mackenzie, Liard, and South Nahanni Rivers, Northwest Territories. The objectives of this work are to use tree-ring data to study flooding, ice-jamming, slumping, alluviation and erosion, permafrost, and climate. This expedition to the Northwest Territories was organized by W.E.S. Henoch, Glaciology Subdivision, Inland Waters Branch, Department of the Environment, and the portion of this project reported here is conducted for the Inland Waters Branch in fulfillment of the contract undertaken for the Environmental Social Program, Northern Pipelines, with additional support from the Faculty of Forestry, University of British Columbia (through NRC Grant No. A-2077 to J.H.G. Smith), and the Western Forest Products Laboratory, Canadian Forestry Service, Department of the Environment.

This material will be presented in two parts. Part I deals with the trees damaged by landslides, ice-jamming, and flooding. Part II reports on crossdating and chronology building; permafrost, flooding, and alluviation in the Mackenzie Delta; and dendroclimatic studies.

PART I

USING TREE DAMAGE TO DATE LANDSLIDES, ICE-JAMMING, AND FLOODING

Introduction

Many species of trees, particularly the conifers, record variations in climate through their response in radial growth of the tree stem. This variation is registered as differences in annual ring width and density in the transverse cross section of branches, roots, and stems. In addition to the general climate, trees may record more localized events, such as landslides, floods, or ice-jamming, through the damage that the tree sustains from injuries resulting from these events. Part I of this report deals with the dating of several landslides along the Mackenzie and Liard Rivers, and the dating of ice-jamming and flooding along the Liard River between Ft. Simpson and Nahanni Butte, by using trees that have been affected by these events.

Four techniques of dating have been used: (1) dating scars on the trunks of trees growing along the banks of the river, that have resulted from damage from ice or driftwood carried by the river during spring ice-jamming or flooding; (2) dating the time the three was pushed into a leaning position, by ice-jamming, flooding, or slumping, through an evaluation of the reaction wood in the cross section of the tree; (3) dating the outermost ring of trees killed by the event by

using the dendrochronological crossdating technique, and (4) estimating the age of young trees, by ring counts, that have grown at the location of the slumping after the event occurred.

This report is to be considered in conjunction with a report on this project by W.E.S. Henoch. Detailed site description and interpretation of geomorphic events are given by Henoch; the major concern of this report is the dating of the samples.

Tree-ring samples were collected from a total of 29 locations (Sites A through CC), but Part I of this report deals with material from 11 sites (Sites A through L, excluding Site C). Some general site data are presented in Table I.

DATING LANDSLIDES ALONG THE MACKENZIE AND LIARD RIVERS

Dendrochronological samples were collected from two areas of slumping on the left bank of the Mackenzie River a few miles downstream from Ft. Simpson and from one large landslide on the right bank of the Liard River between Ft. Simpson and Nahanni Butte.

The Mackenzie River--Spruce Creek Site (Site A)

This site is a landslide on the left bank of the Mackenzie River about 1.2 miles downstream from Spruce Creek. There is evidence that there has been ground movement at different times

and in different directions during the past. The movement of the ground has forced many of the trees at this site into a leaning position (Fig. 1) and caused the formation of compression wood in the stem of the trees (Figs. 2, 3, and 4). The direction of lean and the year the leaning took place can be determined from an examination of the cross sections collected from the trunks of these trees. These data, along with certain other observations, are presented in Figures 5, 6, 7, and 8.

Of the four trees samples, the slumping that took place in 1908 is recorded in three of them, and the slumping that occurred in 1944 is recorded in all four of them.

TABLE I 1972 1984 PING sites, geological supplements

Site	Site Name	Site Location	Collection Date	Cross Sections	Core
A	Mackenzie River-Spruce Creek	Landslide on left bank of Mackenzie River near Spruce Creek	June 8	PSWH-72-1 -- -4	
B	Mackenzie River-Martin River	Landslide on left bank of Mackenzie River near Martin River	June 9	-5 -- -18 (Sections and cores)	
C	Ft. Simpson-Spruce 1	Left bank of Mackenzie River above mouth of Liard River	June 11		PSWH-72-19 -- -33
D	Liard River-Near Mouth	Right bank of Liard River near mouth	June 12	PSWH-72-34 -- -39	
E	Liard River-Top Island	On top Island near head	June 12	-40 -- -42	
F	Liard River-Ferry Landing	Left bank of Liard River at Ft. Simpson Ferry Landing	June 12	-43 -- -45	
G	Liard River-Above Cholo's Place	Left bank Liard River above Jimmie Cholo's Place	June 13	-46 -- -50	
H	Liard River-Below Cholo's Place	Left bank Liard River below Jimmie Cholo's Place	June 13	-51 -- -60	
I	Liard River-Below Rapids	Between Site G and the Liard River Rapids	June 14	-61 -- -63	
J	Liard River-Landslide	Right bank of Liard River at large slump on Liard R. Rapids.	June 14	-64 -- -66 A67X	
K	Liard River-Poplar River	Right bank of Liard River at mouth of Poplar River	June 15	-68 -- -69	-67
L	Liard River-First Island Above Hutton River	At upper end of first island upstream from Hutton River	June 15	-70 -- -71	
M	Nahanni Butte-Spruce 1		June 17	72 -- -87 (Sections and cores)	
N	Nahanni Butte-Spruce 2		June 17	-88 -- -105 (Sections and cores)	
O	South Nahanni River - Larch	Left bank of South Nahanni River at Cadillac Mine Road	June 18		-106 -- -110
P	South Nahanni River-Deadmen Valley	Right bank of South Nahanni River at lower end of Deadmen Valley	June 19		-111 -- -126
Q	Little Doctor Lake - Upper	Nahanni Range near treeline just south of Little Doctor Lake	June 25	-127 -- -135	-136 -- -147
R	Little Doctor Lake - Lower	At base of Nahanni Range near Southwest end of Little Doctor Lake	June 25		-148 -- -153
S	Ft. Simpson - Pine	Road Ft. Simpson-Yellowknife Mile 283	June 26		-154 -- -167
T	Inuvik - Dolomite Lake 1	S.E. shore of Dolomite Lake	July 1		-189 -- -205
U	Arctic Red River	Arctic Mountain House	July 3		-206 -- -219
V	Inuvik - Dolomite Lake 2	N.E. shore of Dolomite Lake	July 9		-220 -- -223
W	Inuvik Airport-Black Spruce	N. shore of Dolomite Lake	July 9	-234 -- -248	
X	Campbell River 1	14.3 km E. from East Channel	July 11	-267	-250 -- -266
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Z	Campbell River 3	15.1 km E. from East Channel	July 11	-269	
AA	Campbell River 4	14.7 km E. from East Channel	July 11	-270	
BB	Campbell River 5	5 km E. from East Channel	July 11	-271	
CC	Ft. Simpson-Spruce 2		June 26		-168 --



a



b

Fig. 1 Spruce trees at Site A with crooked stems (arrows) resulting from being forced into a leaning position by slumping.



a



b

Fig. 2 Compression wood in cross sections taken from spruce trees at Site A: a. PSWH-72-2, b. PSWH-72-4.



Fig. 3. The crown area of PSWH-72-3. The small stem to the right of the picture is the old stem that stood upright before the tree was forced into a leaning position, and the larger stem in the middle of the picture has taken over as the main stem after the slumping.

Fig. 4. Positive print of a radiograph of a 2 mm thick radial section of the juncture of the "old stem" and "new stem" of PSWH-72-3 shown in Figure 3. The arrow points up.

Fig. 5. PSWH-72-1

Site: Mackenzie River--Spruce Creek (Site A)

Location: Landslide on left bank of the Mackenzie River near Spruce Creek.

Longitude: 121° 48' 00" W Latitude: 62° 59' 30" N

Elevation above water level at collection time: _____

Collection date: June 8, 1973 Species: White spruce

Dating:

Pith date: 1881 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Heavy compression wood starting with the ring-year 1908 (Arrow 2), indicating a considerable lean to the northwest.

Heavy compression wood beginning with the ring-year 1944 (Arrow 3), indicating a shift in the lean to the east.

Comments:

Two periods of slumping are indicated by this specimen: one between the 1907 and 1908 growing seasons, and the other between the 1943 and 1944 growing seasons.

The lean of the tree at time of cutting was 33° from the vertical toward the east.

3
2
N
cm 1 2 3 4 5
in 1 2

Fig. 6 PSWH-72-2

Site: Mackenzie River--Spruce Creek (Site A)

Location: Landslide on the left bank of the Mackenzie River near Spruce Creek.

Longitude: 121° 48' 00" W Latitude: 62° 59' 30" N

Elevation above water level at collection time:

Collection date: June 8, 1972 Species: White spruce

Dating:

Pith date: 1872 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:

Last ring-year before injury: 1907

First ring-year after injury: 1908 (Injury on southwest side)

Reaction wood:

Compression wood beginning with the ring-year 1898 indicating slight lean to the north, (Arrow 2).

Heavy compression wood beginning with the ring-year 1908 (Arrow 3) caused by a strong lean of the tree toward the south.

Heavy compression wood starting with the ring-year 1944 (Arrow 4) caused by a lean to the southeast. The tree was leaning 47° to the southeast at time of cutting.

Comments:

The two periods of slumping indicated by PSWH-72-1 also show in this sample, and another shifting of the tree is suggested for the year 1898.

N
cm 1 2 3 4 5
in 1 2
1
2
3
4

Fig. 7 PSWH-72-3

Site: Mackenzie River--Spruce Creek (Site A)

Location: Landslide on left bank of the Mackenzie River near Spruce Creek.

Longitude: 121° 48' 00" W Latitude: 62° 59' 30" N

Elevation above water level at collection time: _____

Collection date: June 8, 1972 Species: White spruce

Dating:

Pith date: 1876 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Heavy compression wood starting with the ring-year 1908 (Arrow 2), indicating a marked lean to the north-northeast.

Heavy compression wood beginning with the ring-year 1944 (Arrow 3), caused by a lean of the tree to the south-southwest.

Comments:

The two periods of slumping, in 1908 and in 1944, are shown by this sample as by PSWH-72-1 and PSWH-72-2.

There also may have been a shift in the direction of lean from south-southwest to south in 1954.

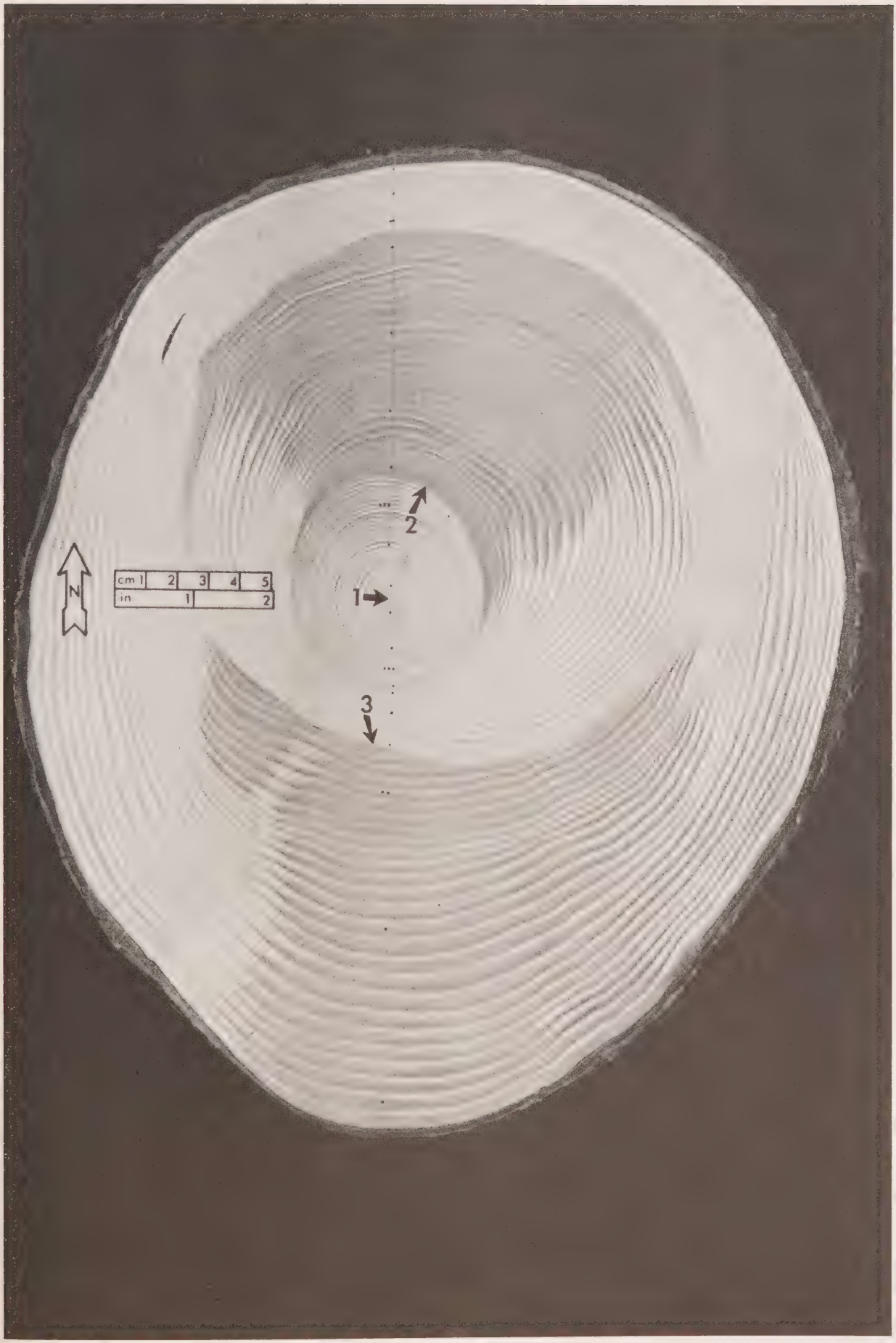

N
cm 1 2 3 4 5
in 1 2
1
2
3

Fig. 8 PSWH-72-4

Site: Mackenzie River--Spruce Creek (Site A)

Location: Landslide on the left bank of the Mackenzie River near Spruce Creek.

Longitude: 121° 48' 00" W Latitude: 62° 59' 30" N

Elevation above water level at collection time: _____

Collection date: June 8, 1972 Species: White spruce

Dating:

Pith date: 1880 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Light compression wood beginning with the ring-year 1905 (Arrow 2). Direction of lean was to the southwest.

Heavy compression wood starting with the ring-year 1914 (Arrow 3) indicating a lean to the southwest.

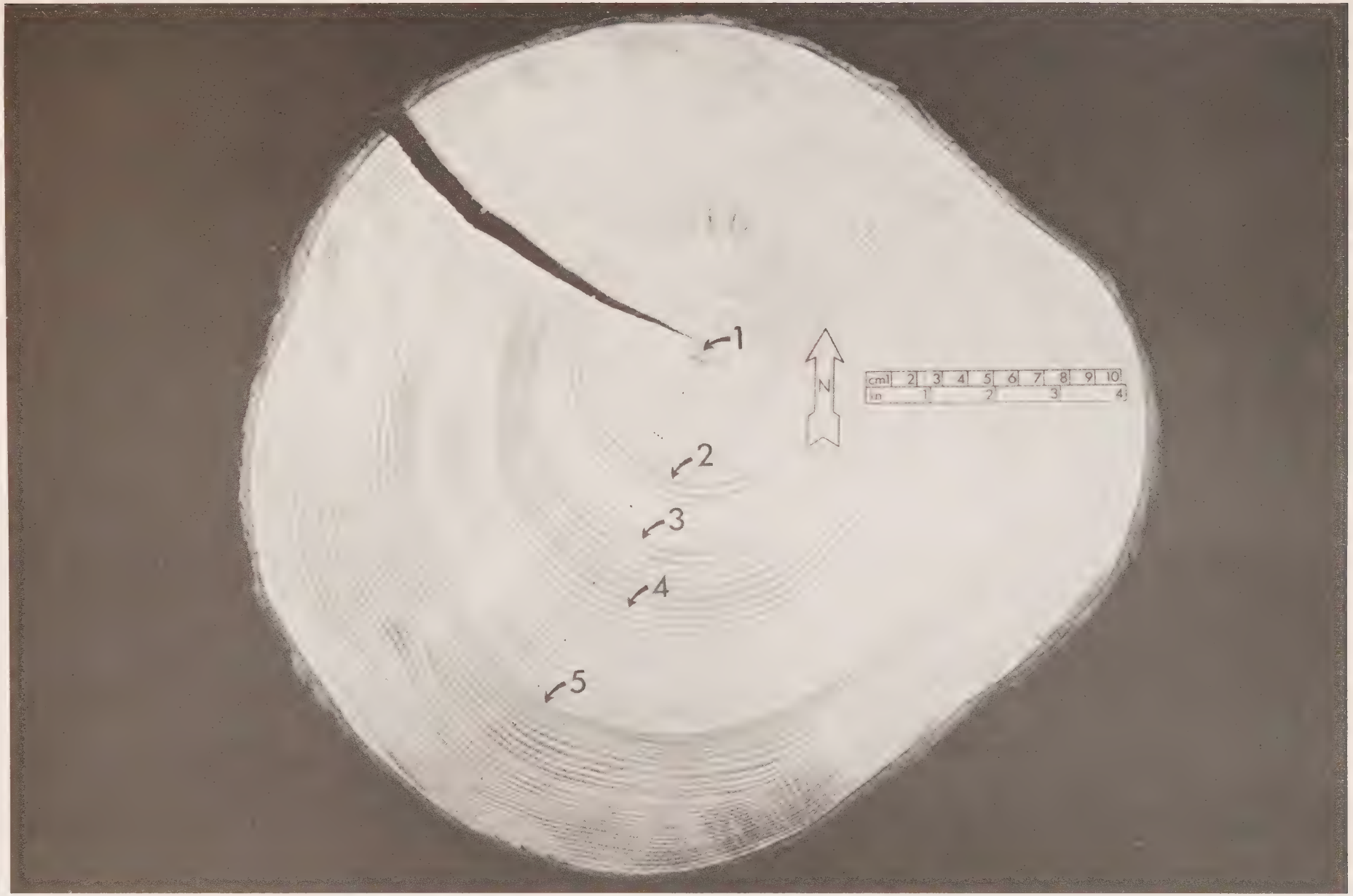
A shift in the location of the compression wood suggests a change in the direction of the lean from the southwest to the south-southwest (Arrow 4) in 1921.

Heavy compression wood starting with the ring-year 1944 indicates a marked lean to the southwest in that year. The tree was leaning 24° to the southwest when it was cut. Arrow 5 points at the 1944 ring-year.

Comments:

This tree was located farther from the river than the other specimens from this site, and the ground surface was apparently less disturbed by this tree.

This tree contains evidence of the 1944 slumping as do the other samples from this site. Also, several different periods of ground movement are indicated by this sample as by the other specimens.


1
2
3
4
5
N
cm 2 3 4 5 6 7 8 9 10
in 1 2 3 4

The Mackenzie River--Martin River Site (Site B)

This site is a large landslide on the left bank of the Mackenzie River about 5 miles downstream from the Martin River. A general view of the slump and the area along the Mackenzie River at this point are shown in Figure 9. Trees growing along the margin of the slump, and leaning toward the landslide area, were sampled in order to date the movement of the ground through an evaluation of the compression wood in these leaning trees (Fig. 10). Dates also were obtained from trees located on the surface of the ground in the middle of the slump area, that had been killed by the landslide; and living trees were sampled in order to provide a tree-ring chronology for dating the dead material (Fig. 11). Several young trees were collected from an area of mud-flow at the base of the slump near the river. These small trees apparently had grown there after one of the most recent movements of the ground surface.

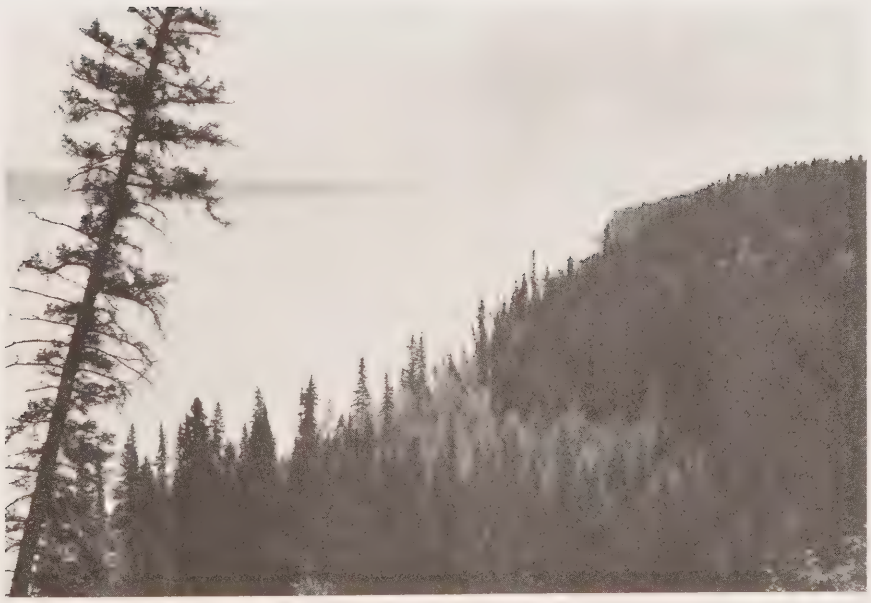
One of the older spruce trees (PSWH-72-14) has recorded in compression wood that it was subjected to a number of periods of ground movement extending throughout its lifetime going back to the mid-1800's. Several of the leaning trees (PSWH-72-5 and -6) and the dead trees in the middle of the landslide area provide dates that indicate that the major slumping at this site took place over a period of several years during the latter half of the 1960's. Five annual rings were counted on the small spruce growing in the mud-flow area, and four rings were found on an aspen from the same area.

Data on the dates, and certain other aspects of the tree-ring samples collected at this site, are presented (Figs. 12-19).

Various aspects of the tree-ring chronologies, such as crossdating and climatic relationships, will be dealt with in Part II, but the crossdating of the material from this site is presented (Fig. 20) in order to show the validity of the dating of the dead trees from the middle of the slump area.



a



b

Fig. 9. The Mackenzie River--Martin River Site. a. Looking up into the slump area from a location near the river. b. Looking up the Mackenzie River from a location near the top of the slump.



a



b

Fig. 10. Leaning trees on the margin of the Mackenzie River--Martin River slump. a. The stump of PSWH-72-5 from which a cross section was taken (Arrow 1); a leaning tree (PSWH-72-6) from which a 5 mm core was taken (Arrow 2); and PSWH-72-14 before it was cut (Arrow 3). b. The stump of PSWH-72-14 showing compression wood on the lower side of the stem toward the direction of lean.



a



b

Fig. 11. Dead trees and living trees used to date the Mackenzie River-Martin River landslide site. a. Dead trees that were killed when they fell into the middle of the slump area. Cross sections were cut (arrows) to be crossdated with living trees at the site. b. Living trees above the landslide area from which 5 mm cores were taken.

Fig. 12. PSWH-72-5

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 61° 57' 30" N

Elevation above water level at collection time: _____

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1850 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Heavy compression wood beginning with the ring-year 1967 (Arrow 2).

Comments:

The areas of slight compression wood near the pith may not be related to any major slumping and were not tabulated.

This tree was leaning toward the slump (29°) at its margin. This leaning apparently took place in 1967.

2
1
cm 1 2 3 4 5
in 1 2
N

Fig. 13. PSWH-72-6

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 61° 57' 30" N

Elevation above water level at collection time:

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1857 (Few rings from pith) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury:

First ring-year after injury:

Reaction wood:

Compression wood beginning with the 1905 ring-year. Heavy compression wood beginning with the 1967 ring-year.

Comments:

A 5 mm core was taken from this tree, bark-to-bark, from the northwest side to the southeast side.

A core does not yield as much information about compression wood as does a complete cross section, but this core does show clearly the compression wood beginning in 1967 as does the tree that was growing near it (PSWH-72-5)


cm

Fig. 14. PSWH-72-14

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 61° 57' 30" N

Elevation above water level at collection time: _____

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1841 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Slight lean toward the northwest beginning with the 1878 ring-year (Arrow 2).

Slight lean to the southwest starting with the 1900 ring-year (Arrow 3).

Lean to the west-northwest in 1912 (Arrow 4).

Lean to the north beginning with the ring-year 1933 (Arrow 5).

Heavy compression wood beginning with the 1949 ring-year (Arrow 6) indicates a considerable leaning of the tree toward the north-northeast in that year.

Comments:

This tree was located on the left (downstream) margin of the slide area and near the lower end of the slide by the river. It was leaning toward the slide.

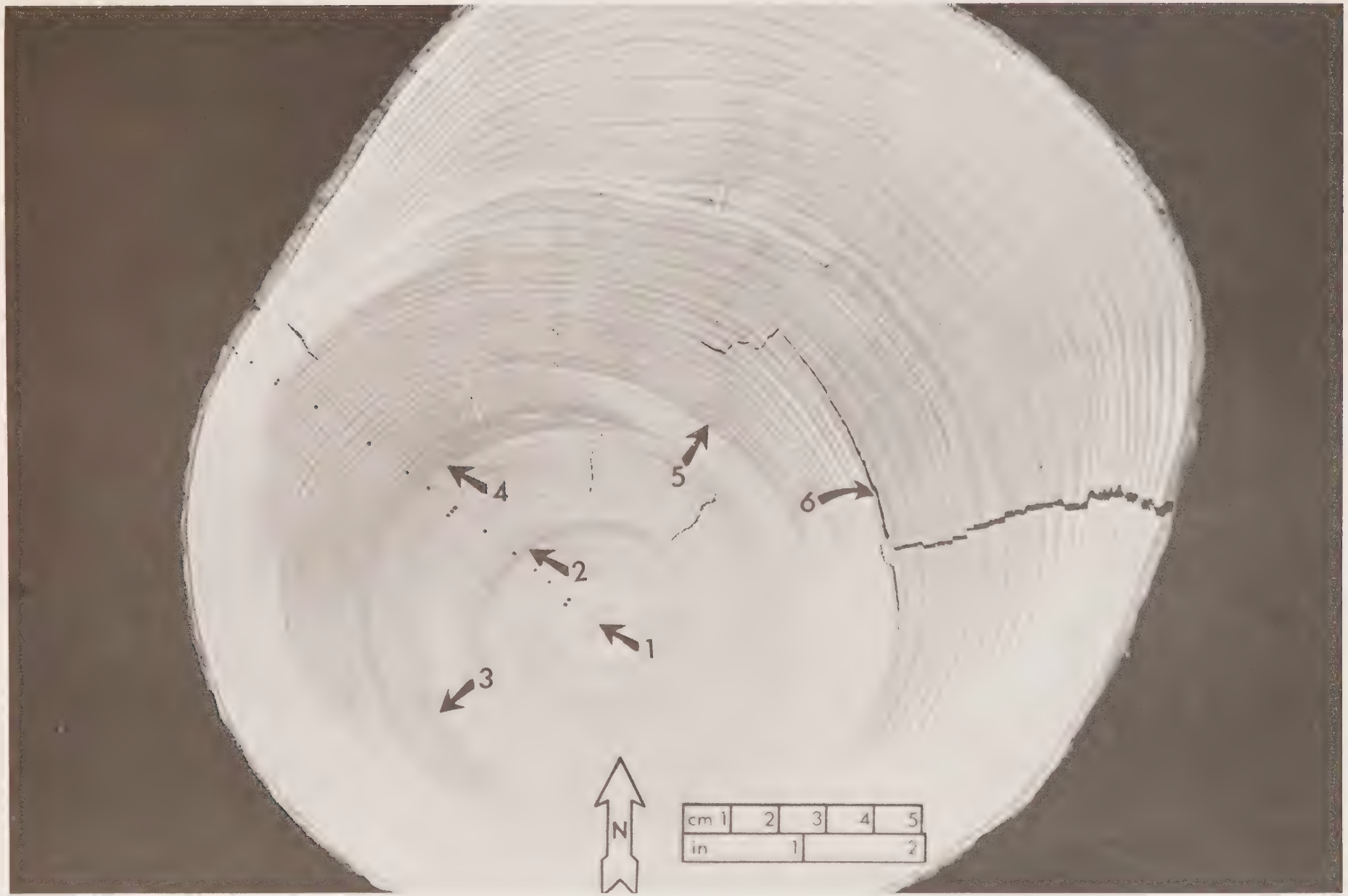

4
5
6
2
1
3
N
cm 1 2 3 4 5
in 1 2

Fig. 15. PSWH-72-9

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 61° 57' 30" N

Elevation above water level at collection time:

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1848 (Arrow 1) Bark date: 1965 (Dead tree, latewood and bark present) (Arrow 2)

Scars:
Last ring-year before injury:

First ring-year after injury:

Reaction wood:

Comments:

This specimen is from a dead tree located on the surface of the ground in the middle of the slide area, within a few feet of PSWH-72-10 and PSWH-72-11. These trees were apparently killed by the landslide and all give a date of 1965 for the last annual ring produced before death. This indicates that they were killed between the 1965 and 1966 growing seasons.

All of the dead samples collected from the middle of the slide area are free from compression wood. This means that they grew in an upright, undisturbed position until they were killed by the landslide.


1
2
cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4

Fig. 16 PSWH-72-10

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 61° 57' 30" N

Elevation above water level at collection time:

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1854 (Arrow 1) Bark date: 1965 (Arrow 2) (Dead latewood and bark present)

Scars:
Last ring-year before injury:

First ring-year after injury:

Reaction wood:

Comments:

This specimen was collected from a dead tree found in the middle of the slide area. It was apparently killed by a landslide that occurred between the 1965 and 1966 growing seasons.

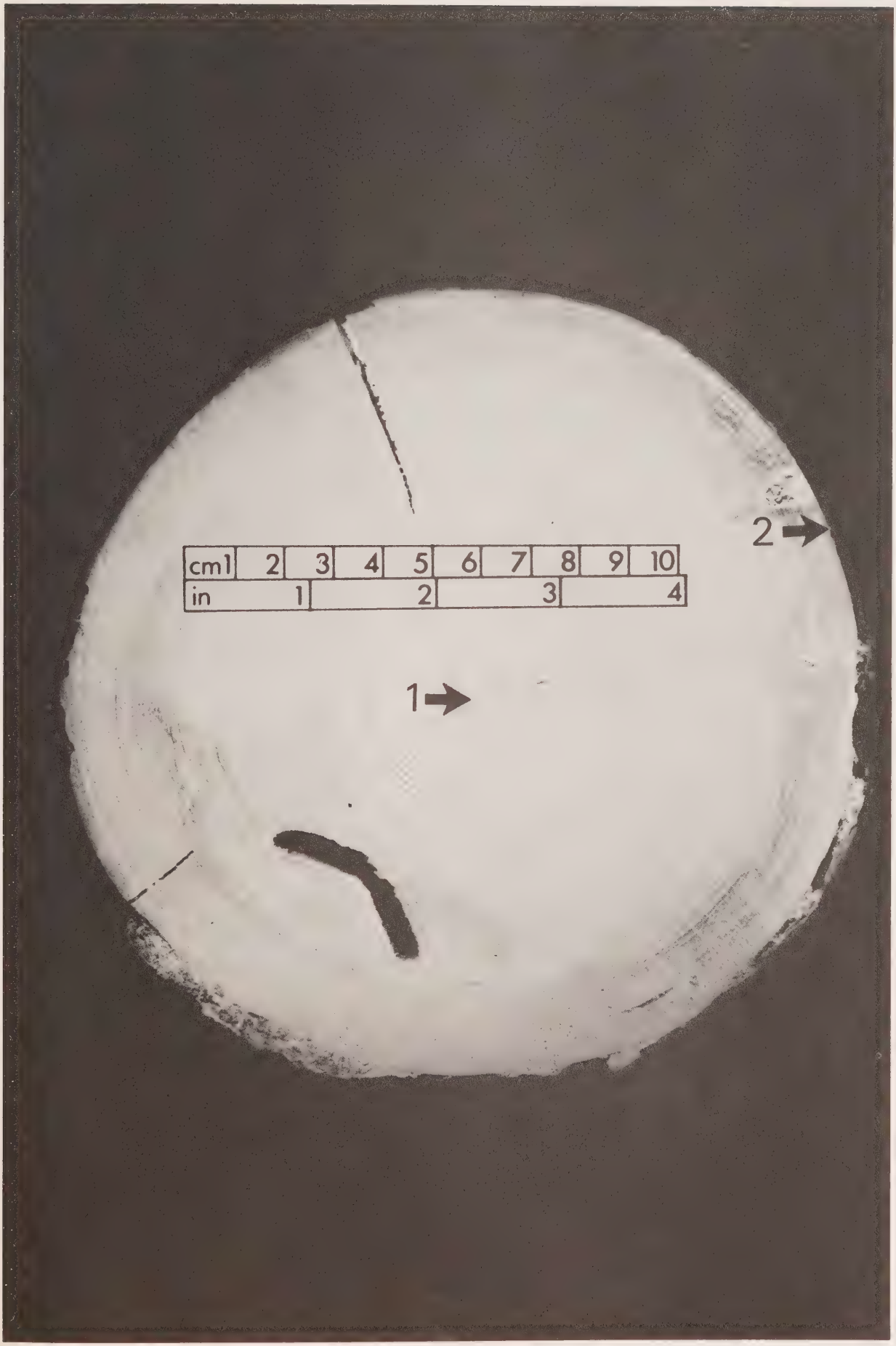

cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4
1
2

Fig. 17. PSWH-72-11

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 60° 57' 30" N

Elevation above water level at collection time: _____

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1886 (Arrow 1) Bark date: 1965 (Arrow 2) (Dead, latewood and bark present)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Comments:

This sample was collected from a dead tree found in the middle of the slide area. It was apparently killed by a landslide that occurred between the 1965 and 1966 growing seasons for white spruce in the area.


1
2
cm 1 2 3 4 5 6 7 8
in 1 2 3

Fig. 18. PSWH-72-12

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 61° 57' 30" N

Elevation above water level at collection time: _____

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1863 (Arrow 1) Bark date: 1965 (Arrow 2) (Dead, bark present but no latewood present)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Comments:

This tree, and PSWH-72-13, were dead trees located on the surface of the ground near the left (downstream) side of the slide area, and the same distance from the river as were the other dead trees collected, PSWH-72-9, PSWH-72-10, and PSWH-72-11.

This tree apparently fell into the slide area and was killed in 1965 during its growing season.


2
1
cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4

Fig. 19. PSWH-72-13

Site: Mackenzie River--Martin River (Site B)

Location: Landslide on the left bank of the Mackenzie River near Martin River.

Longitude: 121° 41' 30" W Latitude: 61° 57' 30" N

Elevation above water level at collection time: _____

Collection date: June 9, 1972 Species: White spruce

Dating:

Pith date: 1865 (Arrow 1) Bark date: 1965 (Arrow 2) (Dead, bark present but no latewood present)

Scars:
Last ring-year before injury: _____

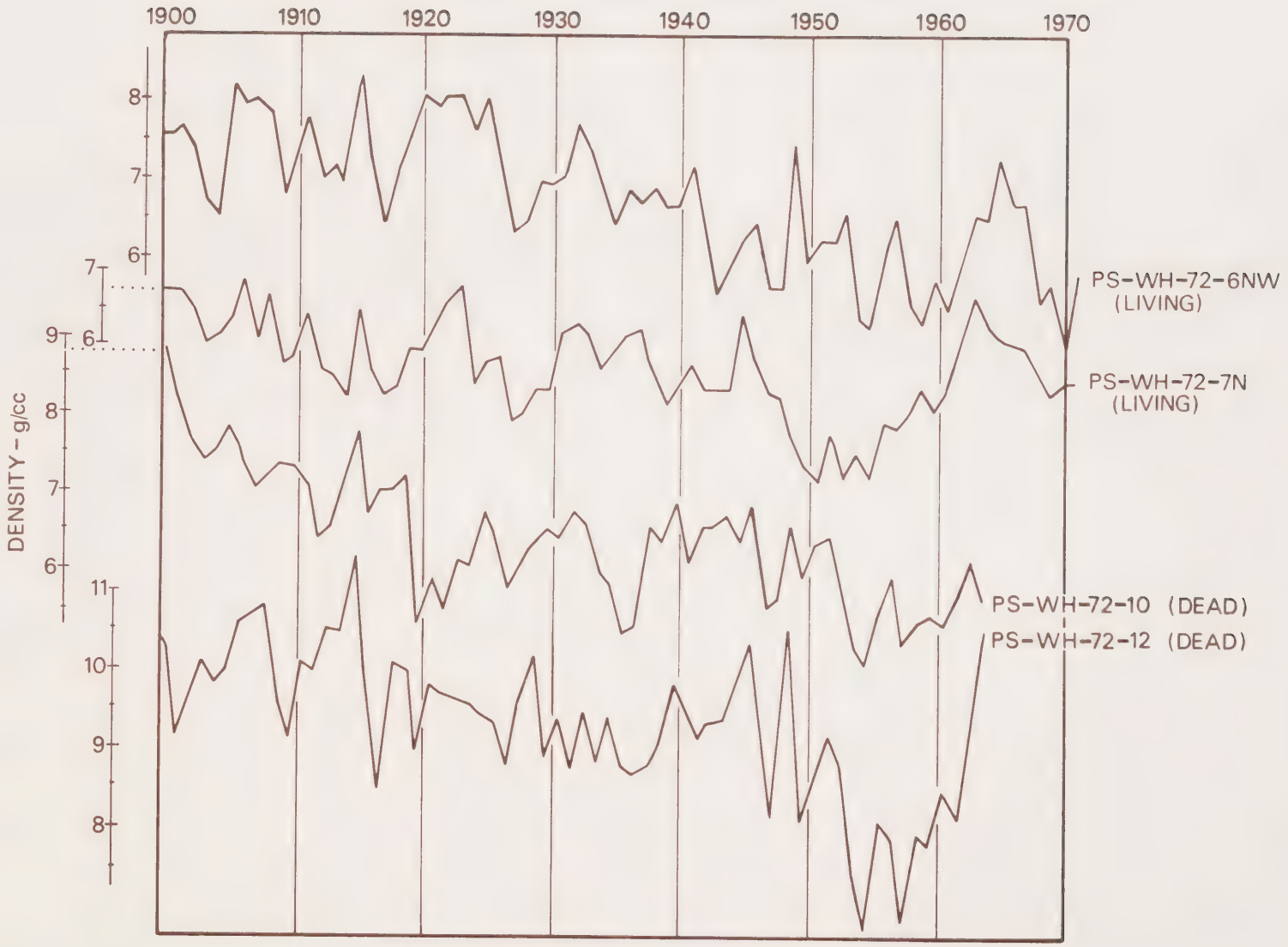
First ring-year after injury: _____

Reaction wood:

Comments:

This tree apparently fell into the slide area and was killed during its growing season in 1965.


2
1
cm 1 2 3 4 5 6 7 8 9 10 11 12 13 14
in 1 2 3 4 5


1900
1910
1920
1930
1940
1950
1960
1970
DENSITY - g/cc
8
7
6
7
6
9
8
7
6
11
10
9
8
PS-WH-72-6NW
(LIVING)
PS-WH-72-7N
(LIVING)
PS-WH-72-10 (DEAD)
PS-WH-72-12 (DEAD)

Liard River--Landslide (Site J)

This large landslide is located on the right bank of the Liard River at the rapids between the Poplar River and the mouth of the Liard. The general appearance of the slump and the surrounding area are shown in Figures 21-25.

Cross sections from four young spruce trees located in the disturbed portion of the slide, were collected (Figs. 26-29). These samples indicate that there was major slumping in 1969 and 1970.



a



b

Fig. 21. Big slump by Liard River rapids.
a. Looking toward the top of the landslide area from the middle of the slump area.
b. Looking at the lower portion of the slump and across the river from the top of the slump.



a



b

Fig. 22. The Liard River Slump.
a. Looking upstream from the slump.
b. Looking downstream from the slump.



a



b

Fig. 23. a. and b. A young spruce tree (PSWH-72-64) located in the middle of the landslide area. The arrows indicate the location on the stem from which a cross section was cut.



a



b

Fig. 24. PSWH-72-66 (Arrow 1) and PSWH-72-67X (Arrow 2).
a. Looking downslope at stumps (Arrows).
b. Looking in a downstream direction at these two young spruce trees before they were cut.



Fig. 25. Recent exposure at the top of the Liard River slump.

Fig. 26. PSWH-72-64

Site: Liard-River--Landslide (Site J)

Location: Right bank of Liard River on large slump on Liard River rapids.

Longitude: 121° 35' 00" W Latitude: 61° 25' 30" N

Elevation above water level at collection time: 145 feet

Collection date: June 14, 1972 Species: White spruce

Dating:

Pith date: 1941 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Slight lean to the northeast in 1957 (Arrow 2).

Slight lean to the northeast in 1965 (Arrow 3).

Heavy compression wood beginning with the 1969 ring-year (Arrow 4) indicates that major leaning of the tree took place between the 1968 and 1969 growing seasons.

Comments:

The section was cut 5 feet up the stem from the base of the tree.

The tree was located in the middle of the slump area.


N
cm 1 2 3 4 5
in 1 2
1
2
3
4

Fig. 27. PSWH-72-65

Site: Liard River--Landslide (Site J)

Location: Right bank of the Liard River on the large slump on the Liard River rapids.

Longitude: 121° 35' 00" W Latitude: 61° 25' 30" N

Elevation above water level at collection time: _____

Collection date: June 14, 1972 Species: White spruce

Dating:

Pith date: 1939 (Arrow 1) Bark date: 1972 (Earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Slight lean in 1969 (Arrow 2).

Heavy compression wood beginning with the 1970 ring-year and this probably represents the time when the tree fell to the ground (Arrow 3).

Comments:

The tree was on the surface of the ground with the crown pointed downhill, but it still had living branches with needles.

The samples was taken 4 feet from the base of the tree.

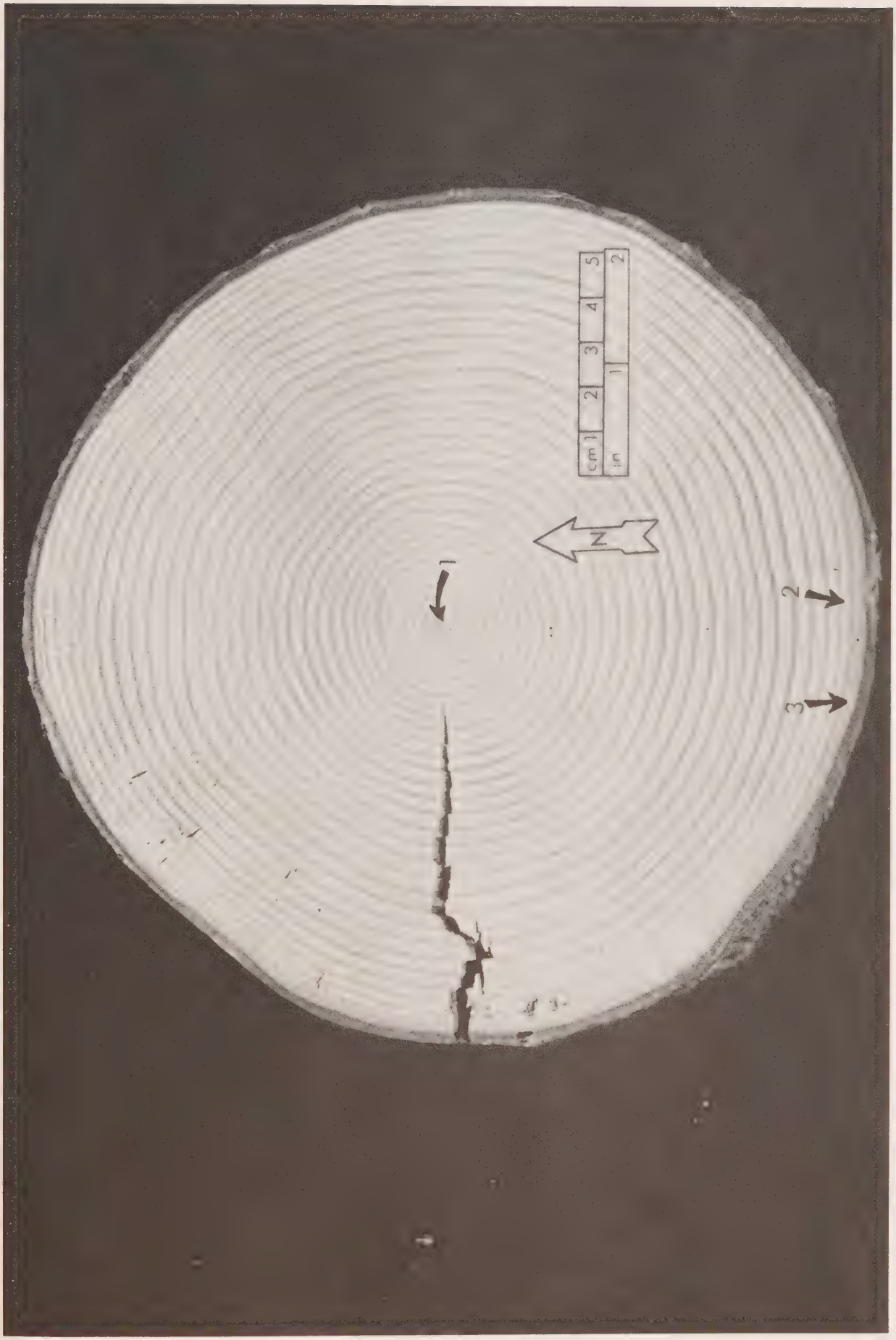

cm
in
N
1
2
3

Fig. 28. PSWH-72-66

Site: Liard River--Landslide (Site J)

Location: Right bank of the Liard River on the large slump on the Liard River rapids.

Longitude: 121° 35' 00" W Latitude: 61° 25' 30" N

Elevation above water level at collection time:

Collection date: June 14, 1972 Species: White spruce

Dating:

Pith date: 1935 (Arrow 1) Bark date: 1972 (Earlywood cells only)

Scars:
Last ring-year before injury:

First ring-year after injury:

Reaction wood:

Slight lean in 1969 (Arrow 2).

Major lean in 1970 (Arrow 3).

Comments:

This tree was leaning downhill toward the river but the compression wood was located on the sideslope side of the stem rather than the downhill side of the tree as might be expected. This suggests that the most recent leaning of the tree had not been recorded in the cross section of the tree as compression wood, because it occurred after the 1971 growing season. This was also the case for another small spruce tree (PSWH-72-67X) that was growing a few feet from this tree.


cm 1 2
in 1
N
1
2
3

Fig. 29. PSWH-72-67X.

Site: Liard-River--Landslide (Site J)

Location: Right bank of the Liard River on the large slump on the Liard River rapids.

Longitude: 121° 35' 00" W Latitude: 61° 25' 30" N

Elevation above water level at collection time: _____

Collection date: June 14, 1972 Species: White spruce

Dating:

Pith date: 1936 (Arrow 1) Bark date: 1972 (Earlywood cells only)

Scars:

Last ring-year before injury: _____

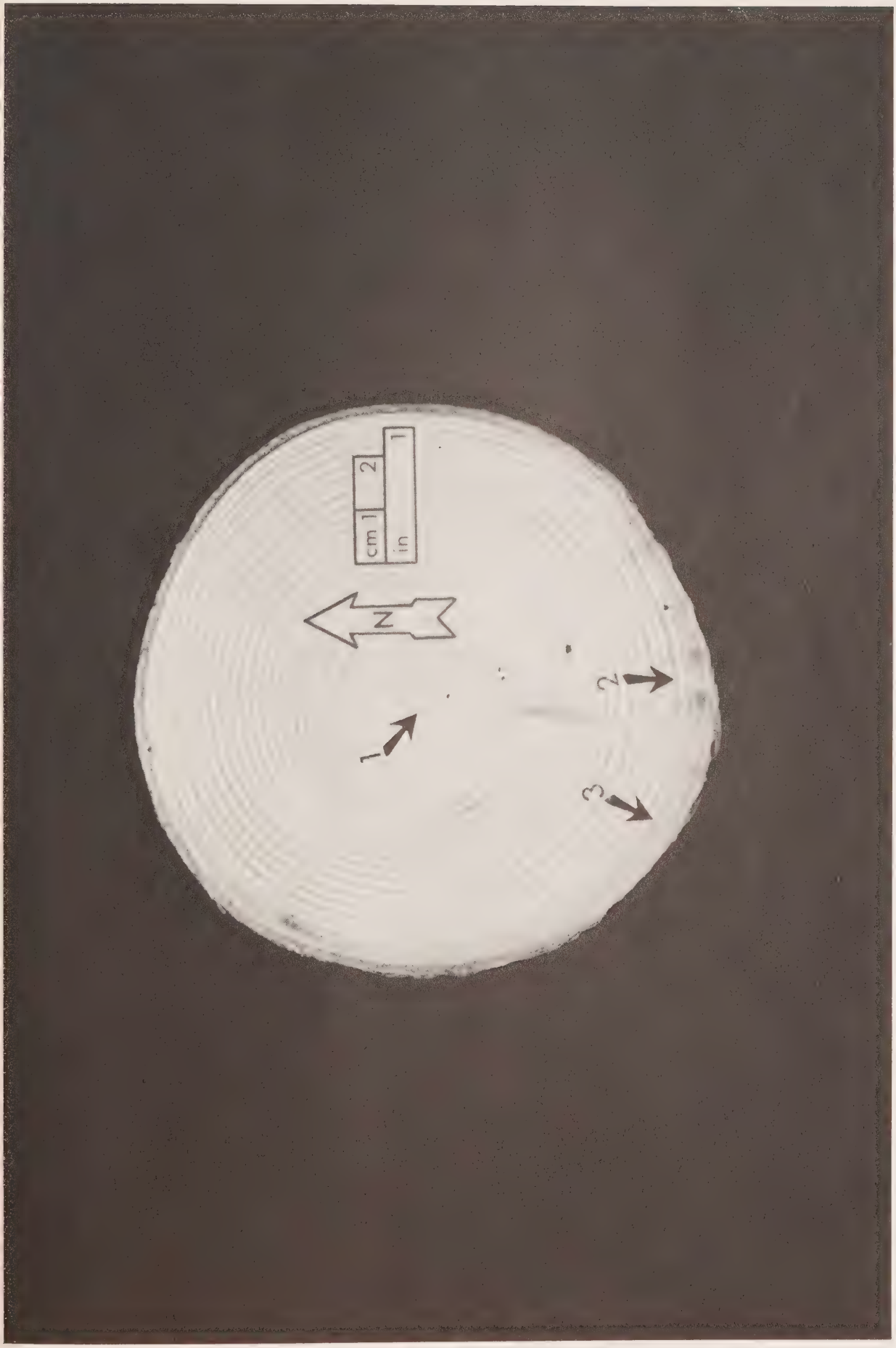
First ring-year after injury: _____

Reaction wood:

Slight lean in 1969 (Arrow 2).

Major lean in 1970 (Arrow 3).

Comments:


cm
in
N
1
2
3

DATING ICE-JAMMING AND FLOODING ALONG THE LIARD RIVER

Dendrochronological samples were collected from eight different locations along the Liard River between Nahanni Butte and Ft. Simpson for the purpose of determining the time and levels of flooding and ice-jamming in the past. Ice-jamming and the largest floods occur on this river during the spring. The technique used was to locate trees on islands in the river and along the river banks that had been damaged by driftwood or ice carried down the river. The damage incurred by the tree is recorded in the annual rings as a scar if the tree is struck by ice or driftwood, and as reaction wood if the tree is pushed into a leaning position by water, ice or drift. The annual rings record the time, and the elevation of the damaged tree above the water level indicates the extent, of the flooding or ice-jamming.

Damage resulting in scars or the pushing of the trees into a leaning position may be caused by factors other than ice-jamming or flooding, but the trees collected were selected from areas where these events apparently had occurred. Confirmation that a particular event such as a spring flood actually occurred during a particular year, comes from the number of samples that record that event as scars or reaction wood. The date of an injury on a single sample for a particular year may be discounted, but if the same year is recorded on a number of samples, the probability is increased that an actual event, such as a spring flood, is being recorded.

The judgement as to whether damage to a particular tree has been caused by flooding or ice-jamming is the responsibility

of Henoch and will be dealt with in his report; but in this paper we consider the cause to be flooding if the trees apparently are pushed over by large pieces of driftwood, we consider it to be ice-jamming if the injured trees are located high on the river bank, and ice-jamming or flooding if the scarred trees are located near the water.

The format followed in presenting this material is to give a brief description of the site with a number of site photographs in order to convey a general image of the site appearance; and to present photographs, with data on the dating of tree damage, of all of the dated samples from the sites.

Liard River--Near Mouth (Site D)

This site is located on the right bank of the Liard River about one mile from its mouth and opposite Top Island. Driftwood is scattered among the trees and most of the trees are scarred or leaning (Fig. 30). The trees that were collected were located about 20 feet above the level of the river.

The four trees that were dated from this site show a complex history of injury (Figs. 31-35). Most of the samples show evidence of injuries that probably occurred during the spring of 1922, 1934, and 1963.



a



b

Fig. 30. a., b., c., and d. Scarred and leaning trees at the site (Site D) near the mouth of the Liard River.



c



d

Fig. 30 (Continued)

Fig. 31. PSWH-72-34

Site: Liard River--Near Mouth (Site D)

Location: Right bank of the Liard River near its mouth.

Longitude: 121° 15' 45" W Latitude: 61° 48' 55" N

Elevation above water level at collection time: 19 feet at base of the tree

Collection date: June 12, 1972 Species: White spruce

Dating:

Pith date: 1890 (Arrow 1) Bark date: 1972 (Some earlywood cells only)

Scars:

Last ring-year before injury: 1936 (Arrow 5) see Comments below; 1956 (Arrow 6); 1962 (Arrow 8).

First ring-year after injury: 1937 (??) see below; 1957 (Arrow 7) 1963 (Arrow 9).

Reaction wood:

Lean to the north-northwest in 1916 (Arrow 2).
Lean to the southeast in 1922 (Arrow 3).
Marked lean to the south in 1934 (Arrow 4).
Strong lean to the south in 1963 (Arrow 9) that lasted until the tree was cut.

Comments:

This small spruce tree was scarred and pushed into a leaning position a number of times in the past by ice or driftwood. The scars extended from 14 to 41 inches above the ground.

The large scar on the north side of the tree (Arrow 5) may have resulted from damage that occurred between the 1936 and 1937 growing seasons, but more probably, it is the result of damage sustained when the tree was pushed into a leaning position in 1934 (Arrow 4). The scar may have expanded in size after 1934 and the annual rings 1934, 1935 and 1936 may have grown on the margin of the scar before its expansion and the death of the cambium in that area.

cm 1
2
in
1
2
3
4
5
6
7
8
9
N

Fig. 32. PSWH-72-35.

Site: Liard River--Near Mouth (Site D)

Location: Right bank of the Liard River near its mouth.

Longitude: 121° 15' 45" W Latitude: 61° 48' 55" N

Elevation above water level at collection time: 20 feet at base of tree

Collection date: June 12, 1972 Species: White spruce

Dating:

Pith date: 1887 (Arrow 1) Bark date: 1972 (Some earlywood cells only)

Scars:

Last ring-year before injury: 1904 (Arrow 2)

First ring-year after injury: 1905 (Arrow 3)

Reaction wood:

Slight lean away from the river and slightly downstream in 1922 (Arrow 4).

Slight lean downstream and slightly away from the river in 1934 (Arrow 5).

Comments:

This small spruce tree had a scar that extended from 14 to 53 inches from the ground, and the sample was taken between 39 and 40 inches from the ground.

The tree probably was damaged during a spring flood in 1905 and pushed over to some extent in floods that occurred in 1922 and in 1934.


cm 1 2
in 1
1
2
3
4
5

Fig. 33. PSWH-72-36 Section 1.

Site: Liard River--Near Mouth (Site D)

Location: Right bank of the Liard River near its mouth.

Longitude: 121° 15' 45" W Latitude: 61° 48' 55" N

Elevation above water level at collection time: 19 feet at base of tree

Collection date: June 12, 1972 Species: White spruce

Dating:

Pith date: 1887 (Arrow 1) Bark date: 1972 (Few earlywood cells present)

Scars:

Last ring-year before injury: 1962 (Arrow 7)

First ring-year after injury: 1963 (Arrow 8)

Reaction wood:

Lean to the southeast in 1892 (Arrow 2).
Lean to the northwest in 1895 (Arrow 3).
Abrupt cessation of compression wood with the ring-year 1921 (Arrow 4) and slight compression wood in the 1922 ring-year (Arrow 5). This compression wood in the 1922 ring-year shows more clearly in another section from this tree that is shown in the following figure.
Marked lean of the tree toward the east-southeast in 1934 (Arrow 6)
Lean of the tree to the southeast in 1963 (Arrow 8).
Lean of the tree to the south in 1967 (Arrow 9).

Comments:

The compression wood that occurs near the pith that was formed when the tree was small and young may be of less significance than compression wood formed later in the life of the tree, because the tree would have been more easily pushed into a leaning position when it was young.

This cross section was taken from 8 to 9 inches above the ground through a scar that extended from 5 to 13 inches above the ground.

cm 1
2
in
1
N
1
2
3
4
5
6
8
9

Fig. 34. PSWH-72-36 Section 2.

Site: Liard River--Near Mouth (Site D)

Location: Right bank of the Liard River near its mouth.

Longitude: 121° 15' 45" W Latitude: 61° 48' 55" N

Elevation above water level at collection time: 19 feet at base of tree

Collection date: June 12, 1972 Species: White spruce

Dating:

Pith date: 1889 (Arrow 1) Bark date: 1972 (Few earlywood cells present)

Scars:

Last ring-year before injury: 1962 (Arrow 6)

First ring-year after injury: 1963 (Arrow 7)

Reaction wood:

Lean to the southeast in 1892 (Arrow 2).
Compression wood beginning with the ring-year 1894 suggesting a lean (Arrow 3) to the northwest. (This compression wood does not appear until 1905 in PSWH-72-36 Section 1, but in both samples there is an abrupt end to the compression wood in the 1892 ring-year on the southeast side).
Compression wood beginning with the 1922 ring-year (Arrow 4) indicating a lean to the southeast in that year. (This does not show so clearly in Section 1).
Considerable lean of the tree to the east-southeast in 1934 (Arrow 5).
Lean of the tree to the east-southeast in 1963 (Arrow 7).
Lean of this portion of the tree to the south-southeast in 1967 (Arrow 8).

Comments:

This sample was taken from 30 to 31 inches from the ground through a scar that extended from 13 to 48 inches from the ground.

7
8
5
6
4
1
3
2
cm 1
2
in
1
N

Fig. 35. PSWH-72-37.

Site: Liard River--Near Mouth (Site D)

Location: Right bank of the Liard River near its mouth.

Longitude: 121° 15' 45" W Latitude: 61° 48' 55" N

Elevation above water level at collection time: 20 feet at base of tree

Collection date: June 12, 1972 Species: White spruce

Dating:

Pith date: ------ Bark date: 1972 (Few earlywood cells present)

Scars:

Last ring-year before injury: 1933 (Arrow 1)

First ring-year after injury: 1934 (Arrow 2)

Reaction wood:

Comments:

A wedge-shaped sample was cut from the tree through a scar that extended from ground level to 10 inches above the ground. The pith is not present on the sample taken, but the annual rings extend back to the 1875 ring-year.

The evidence presented by the scar on this tree indicates that it was damaged between the 1933 and 1934 growing seasons, probably by ice or driftwood in the spring in 1934.


2
1
cm
in

The Liard River--Top Island Site (Site E)

This site is located in the grove of deciduous trees near the head of Top Island. Top Island is on the Liard River near its mouth. The trees that were sampled were at an elevation of 32 feet above the river at time of collection. A general view of the site (Fig. 36) and several of the trees collected (Fig. 37) are illustrated.

All three of the trees dated (Figs. 38-41) apparently were pushed into a leaning position by driftwood carried by a flood that occurred in 1934.



Fig. 36. The Liard River--Top Island Site (Site E). The tree-ring samples were collected in the hardwood grove nearer the camera than the spruce in the distant background.



a



b

Fig. 37. Balsam poplar trees collected at the Liard River--Top Island site. a. PSWH-72-40. b. PSWH-72-43 showing the region of tension wood (arrow) on the upper portion of the leaning stem.

Fig. 38. PSWH-72-40 Section 1.

Site: Liard River--Top Island (Site E)

Location: Near the margin of the forested area near the head of Top Island.

Longitude: 121° 16' 35" W Latitude: 61° 49' 20" N

Elevation above water level at collection time: 32 feet

Collection date: June 12, 1972 Species: Balsam poplar

Dating:

Pith date: 1894 (Arrow 1) Bark date: 1971

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

"Normal" rings up to the 1933 ring-year (Arrow 2).

Tension wood beginning with the 1934 ring-year (Arrow 3).

Comments:

This tree, and the other trees collected at this site, apparently had been pushed into a leaning position by large pieces of driftwood carried onto the island by a flood that occurred in 1934.

1
2
3
N
cm 1 2 3 4 5
in 1 2

Fig. 39. PSWH-72-40 Section 2.

Site: Liard River--Top Island (Site E)

Location: Near the margin of the forested area on Top Island near its head.

Longitude: 121° 16' 35" W Latitude: 61° 49' 20" N

Elevation above water level at collection time: 32 feet

Collection date: June 12, 1972 Species: Balsam poplar

Dating:

Pith date: 1894 (Arrow 1) Bark date: 1942 (Arrow 3)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Tension wood beginning with the 1934 ring-year (Arrow 2).

Comments:

This section is from the dead, top portion of the tree.

cm 1
2
in
1
N
1
2
3

Fig. 40. PSWH-72-41.

Site: Liard River--Top Island (Site E)

Location: Near the margin of the forested area on Top Island near its head.

Longitude: 121° 16' 35" W Latitude: 61° 49' 20" N

Elevation above water level at collection time: 32 feet

Collection date: June 12, 1972 Species: Balsam poplar

Dating:

Pith date: 1894 (Arrow 1) Bark date: Probably 1971 but difficult to determine

Scars:
Last ring-year before injury:

First ring-year after injury:

Reaction wood:

Tension wood beginning with the 1934 ring-year (Arrow 2).

Comments:

The annual rings on this sample near the bark are so highly compressed that they are difficult to date, but the rings from the pith to 1933 can be crossdated with the other balsam poplar samples from this site.

This sample offers additional evidence that there was a flood in the spring of 1934 that carried large pieces of driftwood onto this island to a level 32 feet above the level of the river at time of collection.

2
cm 1 2 3 4 5
in 1 2
N

Fig. 41. PSWH-72-42.

Site: Liard River--Top Island (Site E)

Location: Near the margin of the forested area on Top Island near its head.

Longitude: 121° 16' 35" W Latitude: 61° 49' 20" N

Elevation above water level at collection time: 32 feet

Collection date: June 12, 1972 Species: Balsam poplar

Dating:

Pith date: Ca. 1907 (Arrow 1) Bark date: 1971

Scars:
Last ring-year before injury: 1933 (Arrow 3)

First ring-year after injury: 1934 (Arrow 4)

Reaction wood:

Tension wood beginning with the 1934 ring-year (Arrow 2).

Comments:

The scar from the injury sustained between the 1933 and 1934 growing seasons was completely grown over.

Dating of the sample near the pith was difficult because of the rotten wood.

This sample provides additional evidence that flood waters reached a level of at least 32 feet above the collection date level of the Liard River in a flood that occurred in 1934.


N
cm 1 2 3 4 5
in 1 2
1
2
3
4

The Liard River--Ferry Landing Site (Site F)

This site is located on the left bank of the Liard River at the Ft. Simpson Ferry Landing. Three trees, two white spruce and one balsam poplar, were standing in a row a few feet from one another (Fig. 42). Each had a scar extending from the base of the tree to about 6 feet above the ground. The scar on each tree resulted from injury sustained between the 1925 and 1926 growing seasons (Figs. 43-45). The trees were standing at an elevation 22 feet above the level of the river at the time of collection and ice-jamming or flooding at that level is inferred for the spring of 1926.



Fig. 42. The two scarred white spruce trees and the scarred balsam poplar tree at the Liard River--Ferry Landing site. All three trees were injured between the 1925 and 1926 growing seasons.

Fig. 43. PSWH-72-43.

Site: Liard River--Ferry Landing (Site F)

Location: Left bank of the Liard River at the Ft. Simpson ferry landing.

Longitude: 121° 13' 35" W Latitude: 61° 44' 50" N

Elevation above water level at collection time: 22 feet at ground level

Collection date: June 12, 1972 Species: White spruce

Dating:

Pith date: 1867 (Arrow 1) (Few rings from pith) Bark date: 1972 (Few earlywood cells only)

Scars:

Last ring-year before injury: 1925 (Arrow 2)

First ring-year after injury: 1926 (Arrow 3)

Reaction wood:

Comments:

This tree, and the other two trees from this site (PSWH-72-44 and ...-45), each had a scar on the side of the tree facing the river that extended from ground level to about 6 feet above the ground. All three of these trees were apparently damaged by flooding or ice-jamming that occurred in the spring of 1926.

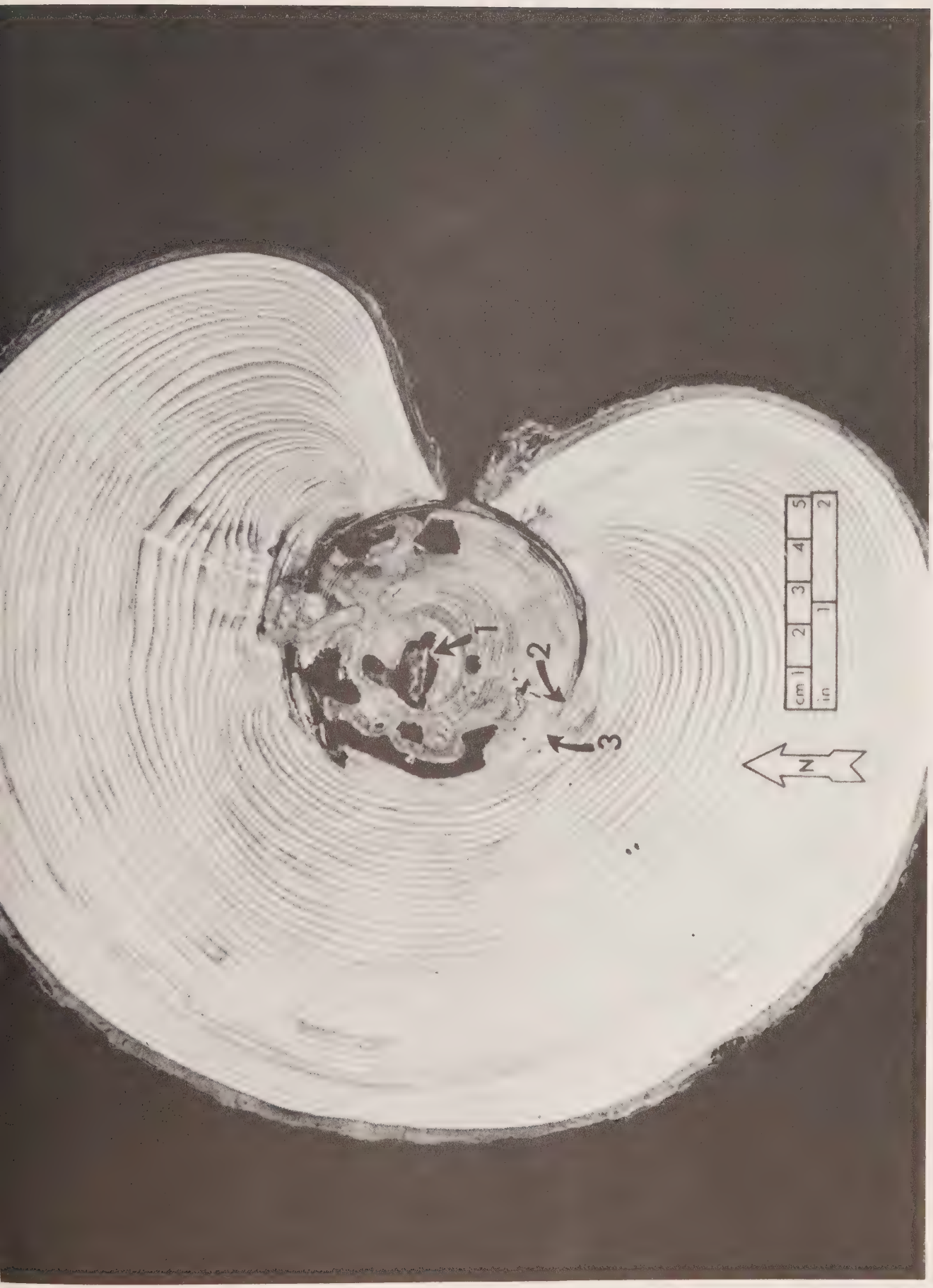

1
2
3
N
cm 1 2 3 4 5
in 1 2

Fig. 44. PSWH-72-44.

Site: Liard River--Ferry Landing (Site F)

Location: Left bank of the Liard River at the Ft. Simpson ferry landing.

Longitude: 121° 13' 35" W Latitude: 61° 44' 50" N

Elevation above water level at collection time: 22 feet at ground level

Collection date: June 12, 1972 Species: Balsam poplar

Dating:

Pith date: Unknown--rotten center Bark date: 1971

Scars:
Last ring-year before injury: 1925 (Arrow 1)

First ring-year after injury: 1926 (Arrow 2)

Reaction wood:

Comments:

Very little dendrochronological work has been done on this species, but the annual rings on many of the samples collected from this area are discernible and there is crossdating between samples through the use of ring width and ring density.

The scar on this tree gives the same date as the scars on the two spruce trees that were located a few feet on either side of this balsam poplar. These trees were apparently damaged by flooding or ice-jamming in the spring of 1926.


2
1
N
cm 1 2 3 4 5
in 1 2

Fig. 45. PSWH-72-45.

Site: Liard River--Ferry Landing (Site F)

Location: Left bank of the Liard River at the Ft. Simpson ferry landing.

Longitude: 121° 13' 35" W Latitude: 61° 44' 15" N

Elevation above water level at collection time: 22 feet at ground level

Collection date: June 12, 1972 Species: White spruce

Dating:

Pith date: 1846 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: 1925 (Arrow 3)

First ring-year after injury: 1926 (Arrow 4)

Reaction wood:

Light compression wood beginning with the 1917 ring-year (Arrow 2) and lasting until the tree was injured between the 1925 and 1926 growing seasons.

Comments:

The tree may have been pushed slightly into a leaning position toward the south by a flood or ice-jamming in 1926, but there is not strong evidence for this conclusion.

There is good evidence that this tree, and the other two trees collected at this site, were damaged by flooding or ice-jamming in the spring of 1926.

4
3
1
2
cm
in
N

The Liard River Site above Cholo's Place (Site G)

This site is located on the left bank of the Liard River about one mile upstream from Jimmie Cholo's cabin. Cholo's place is between the Ft. Simpson Ferry Landing and the mouth of the Poplar River. Five white spruce trees from this site were dated (Figs. 46-54) and they provide strong evidence that the damage was sustained by the trees at two times: during the spring of 1934 and during the spring of 1963. The scars on the trees, for both periods of damage, were more than 40 feet above the level of the river at the time of collection.

Fig. 46. PSWH-72-46.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's place.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 40 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1840 (Arrow 1) Bark date: 1972 (Some earlywood cells present)

Scars:
Last ring-year before injury: 1962 (Arrow 2)

First ring-year after injury: 1963 (Arrow 3)

Reaction wood:

Comments:

This tree probably was damaged by ice-jamming in the spring of 1963.


N
cm 1 2 3 4 5
in 1 2
1
2
3

Fig. 47. PSWH-72-47.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's place.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 40 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: Not present Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: 1962 (Arrow 1)

First ring-year after injury: 1963 (Arrow 2)

Reaction wood:

Comments:

The pith is not present on the sample collected and the innermost ring present is 1915.

This tree probably was damaged by ice-jamming in the spring of 1963.


cm 1
2
3
4
5
N

Fig. 48. PSWH-72-48.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 40 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1849 (Arrow 1) Bark date: 1972 (Some earlywood cells only)

Scars:
Last ring-year before injury: 1962 (Arrow 2)

First ring-year after injury: 1963 (Arrow 3)

Reaction wood:

Comments:

This tree probably was damaged by ice-jamming in the spring of 1963.

3
2
1
cm 1 2 3 4 5
in 1 2
N

Fig. 49. PSWH-72-49.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 40 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: Not present Bark date: 1972 (Some earlywood cells present).

Scars:
Last ring-year before injury: 1962 (Arrow 1)

First ring-year after injury: 1963 (Arrow 2)

Reaction wood:

Comments:

The pith is not present on the wedge-shaped sample collected. The innermost ring on the sample is 1901.

This tree probably was damaged by ice-jamming in the spring of 1963.

cm 1 2 3 4 5
in 1 2
N
1
2

Fig. 50. PSWH-72-50 Section 1.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 34 feet at base of tree

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1858 (Arrow 1) Bark date: 1972 (Some earlywood cells only)

Scars:

Last ring-year before injury: 1933 (Arrow 2)

First ring-year after injury: 1934 (Arrow 3)

Reaction wood:

Difficult to interpret.

Comments:

Five sections were taken from this tree at 3.9 feet (Sec. 1), 5.0 feet (Sec. 2), 6.5 feet (Sec. 3), 11.2 feet (Sec. 4), and 12.1 feet (Sec. 5). These samples were collected because the tree had several scars and apparently had been damaged at different times by ice-jamming or flooding.

This section shows damage that probably occurred during the spring of 1934.


1
2
3
N
cm 2 3 4 5 6 7 8 9 10
in 1 2 3 4

Fig. 51. PSWH-72-50 Section 2.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 34 feet at base of tree

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1861 (Arrow 1) Bark date: 1972 (Some earlywood cells only)

Scars:

Last ring-year before injury: 1933 (Arrow 2); 1962 (Arrow 5)

First ring-year after injury: 1934 (Arrow 3); 1963 (Arrow 6)

Reaction wood:

Difficult to interpret.

Comments:

This section was cut 5 feet above ground level.

This section contains evidence of damage that may have resulted from ice-jamming in the spring of 1934 and the spring of 1963.

Two annual rings grew on the margin of the scar after the damage that occurred between the 1933 and 1934 growing seasons, and before the cambium died in that area. This is why the last ring-year before the "grown-over" scar is 1935 (Arrow 4).

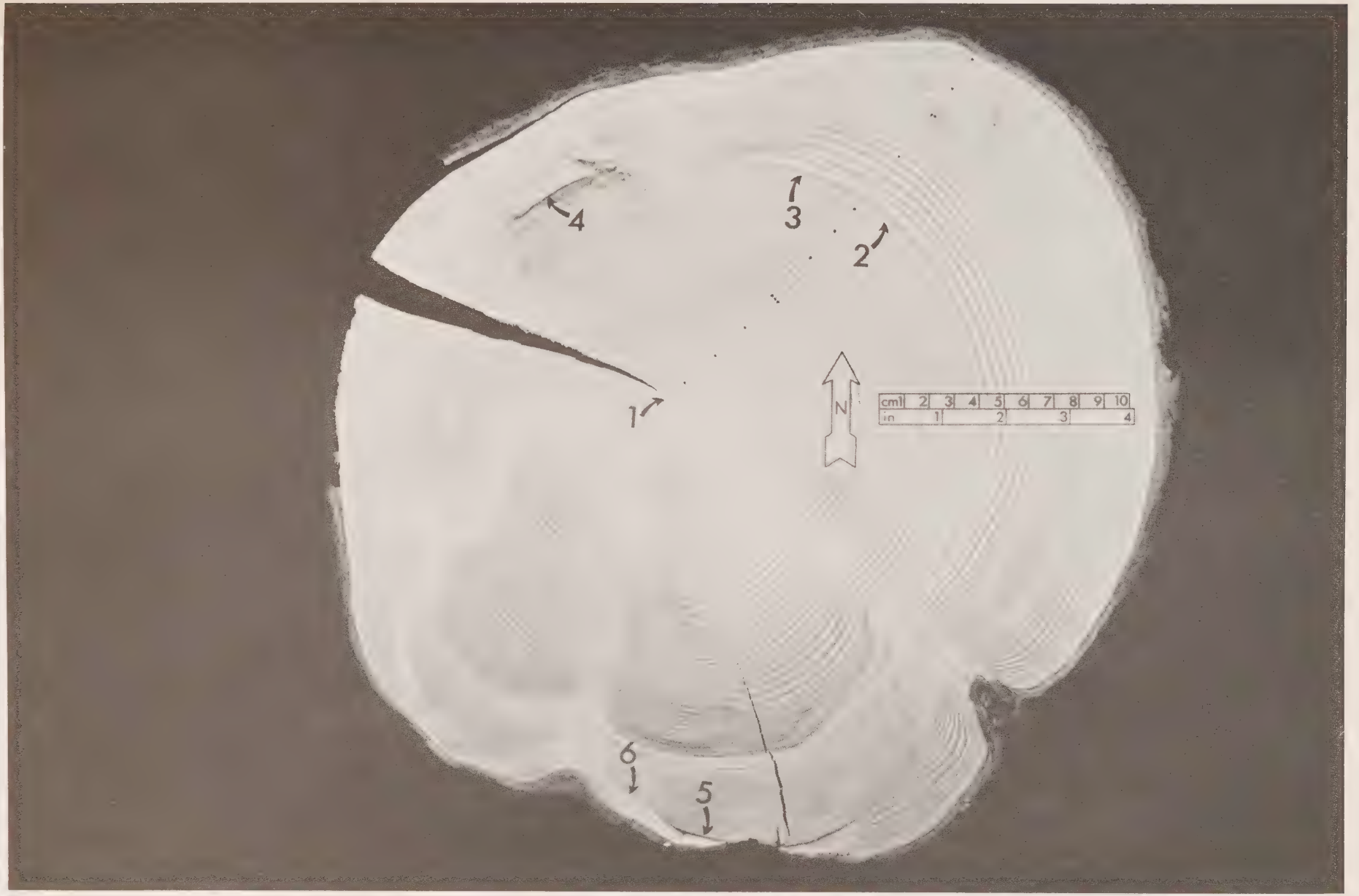

4
3
2
1
N
cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4
6
5

Fig. 52. PSWH-72-50 Section 3.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 34 feet at base of tree

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1864 (Arrow 1) Bark date: 1972 (Some earlywood cells present)

Scars:
Last ring-year before injury: 1933 (Arrow 2)

First ring-year after injury: 1934 (Arrow 3)

Reaction wood:

Difficult to interpret.

Comments:

This section was cut 6.5 feet above ground level.

This sample contains evidence of damage that may have been caused by ice-jamming in the spring of 1934.

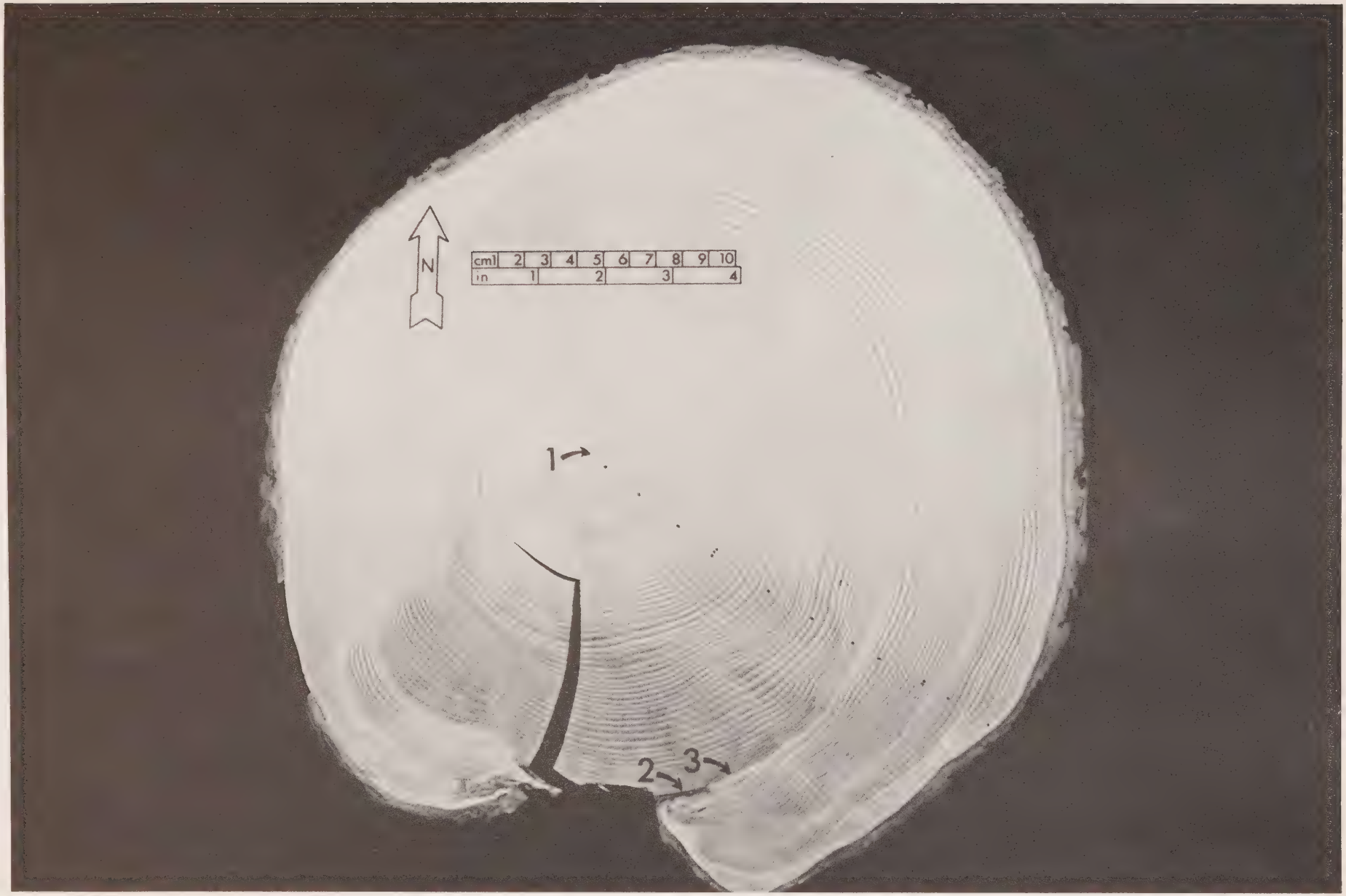

N
cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4
1
2
3

Fig. 53. PSWH-72-50 Section 4.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 34 feet at base of tree

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1873 (Arrow 1) Bark date: 1972 (Some earlywood cells present)

Scars:

Last ring-year before injury: 1933 (Arrow 2)

First ring-year after injury: 1934 (Arrow 3)

Reaction wood:

Comments:

This section was collected 11.2 feet above ground level.

This sample contains evidence of damage that may have been caused by ice-jamming in the spring of 1934.

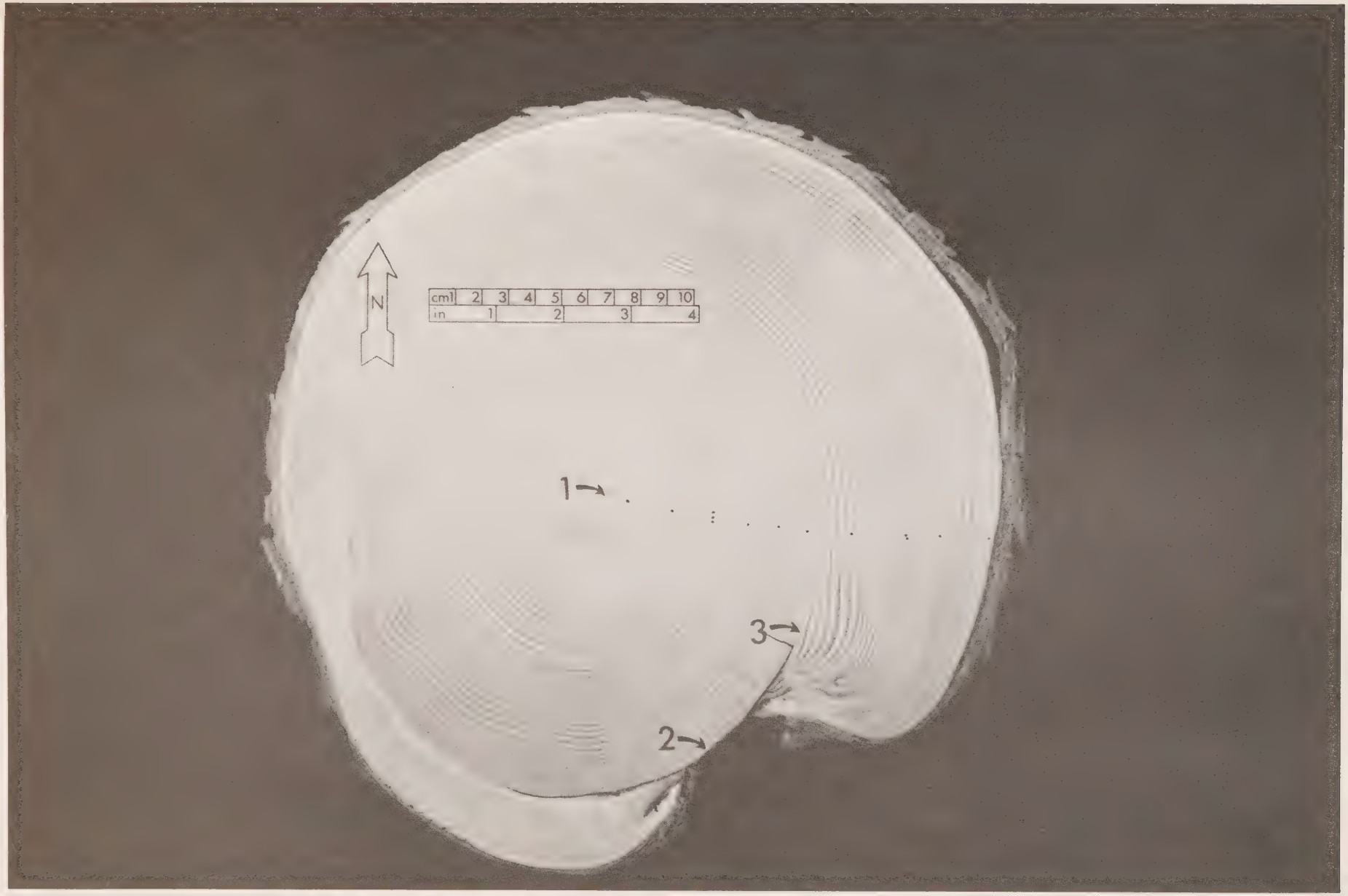

N
cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4
1
2
3

Fig. 54. PSWH-72-50 Section 5.

Site: Liard River--Above Cholo's Place (Site G)

Location: Left bank of the Liard River upstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 38' 10" N

Elevation above water level at collection time: 34 feet at base of tree

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1876 (Arrow 1) Bark date: 1972 (Some earlywood cells present)

Scars:

Last ring-year before injury: 1933 (Arrow 2)

First ring-year after injury: 1934 (Arrow 3)

Reaction wood:

Comments:

This section was taken at the base of the living crown at 12.1 feet above the ground.

This sample contains evidence of damage that may have been caused by ice-jamming in the spring of 1934.

1
2
3
N
cm
2
3
4
5
6
7
8
9
10
in
1
2
3
4

The Liard River Site below Cholo's Place (Site H)

This site is located on the left bank of the Liard River about 1/2 mile downstream from Jimmie Cholo's cabin. Scarred trees were found up to 54 feet above the level of the river at collection time (Figs. 55-56). Four white spruce trees from the site were dated (Figs. 57-60), and all of them were damaged between the 1908 and 1909 growing seasons. This evidence suggests that the trees were damaged by ice-jamming during the spring of 1909.

The elevation of 54 feet above the water for scarred trees is higher than any level for the other sites found on the Liard between Ft. Simpson and Nahanni Butte. This information should be of local significance in that Cholo's cabin, which is very near this site, is only about 33 feet above the river.



a



b

Fig. 55. Ice-scarred trees at the Liard River site below Cholo's cabin, a. Looking up at the site from a location near the edge of the water. b. One of the ice-scarred white spruce trees.



a



b

Fig. 56. Ice-scarred trees up to 54 feet above the Liard River. All trees dated indicate that the injury occurred during the spring of 1909.

Fig. 57. PSWH-72-51.

Site: Liard River--Below Cholo's Place (Site H)

Location: Left bank of the Liard River downstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 39' 20" N

Elevation above water level at collection time: 54 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1847 (Arrow 1) Bark date: 1972 (Some earlywood cells only)

Scars:

Last ring-year before injury: 1908 (Arrow 2)

First ring-year after injury: 1909 (Arrow 3)

Reaction wood:

Comments:

This sample provides evidence that ice-jamming damaged this tree in the spring of 1909 at this site which was 54 feet above the Liard River at the time of collection.


cm 1 2
in 1
N
1
2
3

Fig. 58. PSWH-72-53.

Site: Liard River--Below Cholo's Place (Site H)

Location: Left bank of the Liard River downstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 39' 20" N

Elevation above water level at collection time: 54 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: Not present Bark date: 1972 (Few earlywood cells only)

Scars:

Last ring-year before injury: 1908 (Arrow 1)

First ring-year after injury: 1909 (Arrow 2) (The area of the scar has been destroyed by decay, but the 1909 ring-year has traumatic resin canals)

Reaction wood:

Comments:

This sample provides evidence that ice-jamming damaged this tree in the spring of 1909.

N
2
cm 1 2 3 4 5
in 1 2

Fig. 59. PSWH-72-57.

Site: Liard River--Below Cholo's Place (Site H)

Location: Left bank of the Liard River downstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 39' 20" N

Elevation above water level at collection time: 54 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: 1847 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: 1908 (Arrow 2)

First ring-year after injury: 1909 (Arrow 3)

Reaction wood:

Comments:

This sample provides evidence that ice-jamming damaged this tree in the spring of 1909.

1
2
3
N
cm 1 2
in 1

Fig. 60. PSWH-72-58.

Site: Liard River--Below Cholo's Place (Site H)

Location: Left bank of the Liard River downstream from Jimmie Cholo's cabin.

Longitude: 121° 28' 30" W Latitude: 61° 39' 20" N

Elevation above water level at collection time: 54 feet

Collection date: June 13, 1972 Species: White spruce

Dating:

Pith date: Not present Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: 1908 (Arrow 1)

First ring-year after injury: 1909 (Arrow 2)

Reaction wood:

Comments:

This sample provides evidence that ice-jamming damaged this tree in the spring of 1909.

1
2
N
cm 1
2
1
in

The Liard River Site below the Rapids (Site I)

This site is located on the left bank of the Liard River between Site G and the Liard River rapids. Three white spruce trees, from a location from about 13 to 15 feet above the river, were collected. One of these was dead and on the ground surface. The tree-ring chronology in this specimen is distorted by compression wood and the dating is too tentative to report at this time. Another spruce tree cut at this site was fairly rotten and contained no record of injury. The third tree (PSWH-72-61, Fig. 61), has recorded the flood of 1963 as traumatic resin canals in that ring-year (Fig. 62).



Fig. 61. A scarred white spruce tree located 13.5 feet above the Liard River at Site I.

Fig. 62. PSWH-72-61.

Site: Liard River--Below Rapids (Site I)

Location: Between Site G and the Liard River rapids.

Longitude: 121° 28' 30" W Latitude: 61° 39' 20" N

Elevation above water level at collection time: 23 feet

Collection date: June 14, 1972 Species: White spruce

Dating:

Pith date: 1848 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: 1962 (Arrow 2)

First ring-year after injury: 1963 (Arrow 3)

Reaction wood:

This sample contains compression wood and indicates that the tree leaned in different directions at different times during the past, but interpretation is difficult.

Comments:

The last ring-year before the scar in 1966 (Arrow 4), but the rings after 1962 have traumatic resin canals and are reduced in size, indicating that the injury occurred between the 1962 and 1963 growing seasons. The rings may have continued to grow in this area of the stem of the tree until the death of the cambium in 1966, although the tree had been damaged by a flood or ice-jamming during the spring of 1963.

1
2
3
4
N
cm
in

The Liard River--Poplar River Site (Site K)

This site is located on the right bank of the Liard River several hundred yards downstream from the mouth of the Poplar River. A general view of the Liard in this vicinity is given in Figure 63 and the only tree dated from this site is shown in Figure 64. The heavy compression wood in the cross section of the stem of this tree indicates that it was pushed into a leaning position during the 1905 growing season (Fig. 65).



Fig. 63. View of the Liard River looking upstream from the right bank from a location just below the mouth of the Poplar River.



a



b

Fig. 64. a. and b. A large spruce tree (arrows) with a crooked stem (PSWH-72-68) that was pushed into a leaning position during the 1905 growing season at the Liard River--Poplar River site.

Fig. 65. PSWH-72-68.

Site: Liard River--Poplar River (Site K)

Location: Right bank of Liard River at the mouth of the Poplar River.

Longitude: 121° 51' 15" W Latitude: 61° 22' 00" N

Elevation above water level at collection time: _____

Collection date: June 15, 1972 Species: White spruce

Dating:

Pith date: 1888 (Arrow 1) Bark date: 1972 (Few earlywood cells only)

Scars:
Last ring-year before injury: _____

First ring-year after injury: _____

Reaction wood:

Compression wood beginning with the 1898 ring-year indicating a lean to the north-northeast when the tree was very young (Arrow 2).

Heavy compression wood beginning with the 1905 ring-year (Arrow 3) indicating a considerable lean toward the south in that year. The compression wood does not start until the middle of the growing season.


N
cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4
1
2
3

The Liard River Site on the First Island above Matou River (Site L)

This site is located a few feet from the edge of the water, on the first island upstream from the Matou River, on the Liard River. This site is above the rapids and the trees grow closer to the water's edge (Fig. 66) than they do farther downstream. Dates were obtained from two white spruce trees at this site (Figs. 67-70). These trees have sustained injuries that indicate that they were damaged in the spring of 1957 and the spring of 1964.



Fig. 66. A scarred and distorted white spruce tree (PSWH-72-70) growing near the edge of the water on an island in the Liard River above the rapids.

Fig. 67. PSWH-72-70 Section 1.

Site: Liard River--First Island Above Matou River (Site L)

Location: At the upper end of the first island upstream from Matou River.

Longitude: 122° 28' 30" W Latitude: 61° 17' 30" N

Elevation above water level at collection time: 4 feet at the base of the tree

Collection date: June 15, 1972 Species: White spruce

Dating:

Pith date: 1906 (Arrow 1) Bark date: 1972 (Some earlywood cells present)

Scars:

Last ring-year before injury: 1963 (Arrow 2)

First ring-year after injury: 1964 (Arrow 3)

Reaction wood:

Comments:

This tree was growing near the edge of the water. It had a number of scars on all sides of the stem. Three sections were collected: Section 1 was cut 6 feet above the base of the tree; Section 2, 3 feet above the base of the tree; and Section 3 was cut 1 foot from the base of the tree.

This section shows a scar that has resulted from an injury sustained between the 1963 and 1964 growing seasons.

1
2
3
N
cm
in

Fig. 68. PSWH-72-70 Section 2.

Site: Liard River--First Island Above Matou River (Site L)

Location: At the upper end of the first island upstream from the Matou River.

Longitude: 122° 28' 30" W Latitude: 61° 17' 30" N

Elevation above water level at collection time: 4 feet at the base of the tree

Collection date: June 15, 1972 Species: White spruce

Dating:

Pith date: 1893 (Arrow 1) Bark date: 1972 (Some earlywood cells present)

Scars:

Last ring-year before injury: 1956 (Arrows 3 and 6); 1963 (Arrows 4 and 8)

First ring-year after injury: 1957 (Arrows 2 and 7); 1964 (Arrows 5 and 9)

Reaction wood:

Comments:

This section shows scars that record damage incurred between the 1956 and 1957 growing seasons, and between the 1963 and 1964 growing seasons.

This sample was cut 3 feet above the base of the tree.

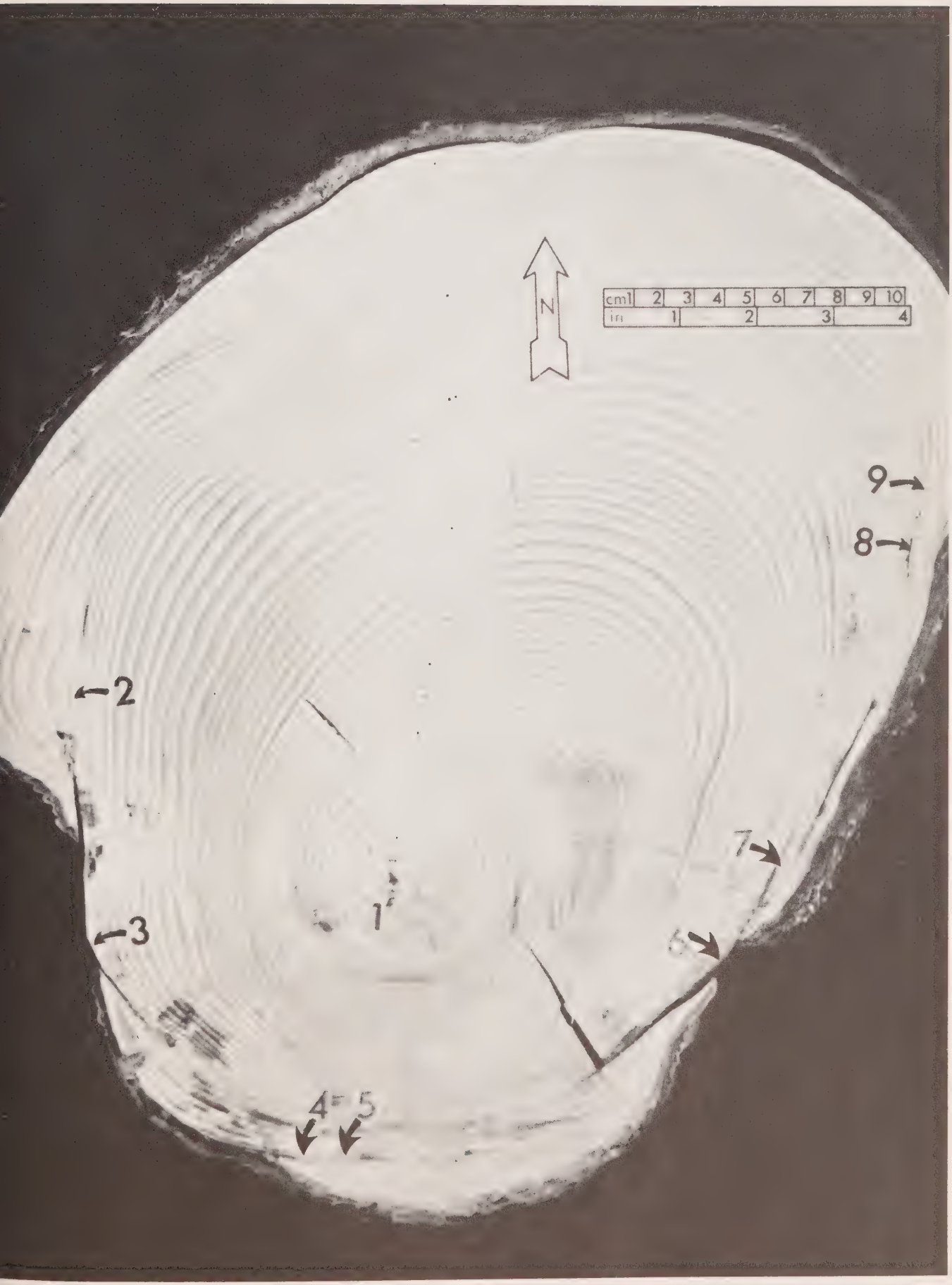

N
cm 1 2 3 4 5 6 7 8 9 10
in 1 2 3 4
9
8
2
7
1
3
6
4
5

Fig. 69. PSWH-72-70 Section 3.

Site: Liard River--First Island Above Matou River (Site L)

Location: At the upper end of the first island upstream from the Matou River.

Longitude: 122° 28' 30" W Latitude: 61° 17' 30" N

Elevation above water level at collection time: 4 feet at the base of the tree

Collection date: June 15, 1972 Species: White spruce

Dating:

Pith date: Not present Bark date: 1972 (Some earlywood cells present)

Scars:
Last ring-year before injury: 1956 (Arrow 1)

First ring-year after injury: 1957 (Arrow 2)

Reaction wood:

Comments:

This sample shows a scar that records damage received between the 1956 and 1957 growing seasons.

It was cut about 1 foot from the base of the tree.


N
cm 1 2 3 4 5
in 1 2
2
1

Fig. 70. PSWH-72-71.

Site: Liard River--First Island Above Matou River (Site L)

Location: At the upper end of the first island upstream from the Matou River.

Longitude: 122° 28' 30" W Latitude: 61° 17' 30" N

Elevation above water level at collection time: 11 feet at top of scar sampled (Section was taken 1 foot below top of scar)

Collection date: June 15, 1972 Species: White spruce

Dating:

Pith date: 1914 (Arrow 1) Bark date: 1972 (Some earlywood cells present)

Scars:

Last ring-year before injury: 1956 (Arrow 2)

First ring-year after injury: 1957 (Arrow 3)

Reaction wood:

Comments:

This tree was 10 feet downstream from PSWH-72-70.

This sample records damage sustained between the 1956 and 1957 growing seasons.

cm 1 2 3 4 5
in 1 2
N
1
2
3

TABLE 2. DATES OF LANDSLIDES, ICE-JAMMING AND FLOODING

| Site | Specimen Number | Type of[1] | Date of the Event that Killed, Scarred, or Pushed the Tree into a Leaning Position | | |

SUMMARY

Tree-ring analysis has been used to determine the dates, and other aspects, of slumping, flooding, and ice-jamming at eleven different locations along the Mackenzie and Liard Rivers. The major portion of this information is contained in the figures showing the photographs of the cross sections of the damaged trees. The most important dates of the events studied are presented in Table 2.

Data from the landslide areas indicate that slumping at each of the sites examined, took place a number of times in the past. However, certain periods of major slumping are inferred, i.e., in 1908 and 1944 at Site A; in 1965-67 at Site B; and in 1969-70 at Site J.

The scars and reaction wood of the trees located at eight sites along the Liard River reveal a complex history of flooding and ice-jamming. The most important events are: (1) ice-jamming in 1909 up to an elevation of 54 feet above the Liard River for its water level on the date of collection; (2) major flooding and ice-jamming in 1934 that damaged trees at a number of locations along the Liard between the rapids and Ft. Simpson; and (3) major flooding and ice-jamming in 1963 that also injured trees at sites along this stretch of the river.

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SUSCEPTIBILITY TO FROST HEAVING OF SOILS at SELECTED SITES ALONG THE LIARD RIVER VALLEY, DETERMINED BY PORE PRESSURE MEASUREMENTS

by

James A. Riddle

Technical Report 11 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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Sampling depth 0.6 m

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12 - Ferry, N.W. shore Liard River
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14 - Liard slump
15 - Swan Point
16 - Right bank Liard, opposite Swan Point

Sampling depth 1.2 m

Figure 17 - Mackenzie north shore
18 - Martin Island
19 - Mackenzie south shore
20 - Ferry, N.W. shore Liard River
21 - Ferry, S.E. shore Liard River
22 - Liard slump
23 - Swan Point
24 - Right bank Liard opposite Swan Point

Summary

The susceptibility to frost heave or ice lensing of different soil types is an important engineering factor that must be dealt with quantitatively for proper pipeline location in the North. This paper illustrates the usefulness of quantitative frost susceptibility criteria, using soils gathered along the Liard River Valley. The soils were collected at possible river pipelines crossing sites. The relative merits of these sites for pipeline crossing are discussed.

The standard testing procedure for frost susceptibility, as used in conventional engineering practices today, is by grain size analysis. However, a new experimental technique developed by the author employing thermo-electric cooling for direct freezing of the sample, makes possible a new, more efficient testing procedure. A soil sample is rapidly frozen and the resultant negative pore pressures at the frost line are measured. This suction is indicative of that soil's capability to cause water to migrate to the frost line, where it freezes resulting in frost heave. It is this surface heave, caused by ice lensing in the sub-soil below, which causes major damage to highway, building, pipeline, and other surface construction.

DEFINITIONS
(Williams, 1968a)

Frost Line: The boundary between frozen and unfrozen soil.

Negative Pore Pressure: Pore water pressure less than atmospheric.

Pore Water Pressure: Pressure of water in pores of soil, or pressure of water external to soil pores but continuous with it and at the same pressure.

Saturated Soil: Soil, the pores of which are filled with water and/or ice. Pores at the surface of the soil are also considered completely filled, so that there is no curvature at the air-water or air-ice interfaces. Scattered entrapped air bubbles within the soil pores are ignored.

Sub-Freezing Temperature: Temperatures below 0° measured on the Centigrade scale. 'Increasing sub-freezing temperature' refers to a state of cooling.

Suction: (1) The difference between the pore water pressure and the air pressure external to the soil as a result of curvature of the air-water interfaces. If the external air pressure is atmospheric the suction is numerically equal to the negative pore pressure. Some authors, referred to in the text, use the term in a more general sense to describe the potential or free energy of the soil moisture.

(2) The difference in pressure between the ice and water in a frozen soil, due to the curvature of the ice-water interfaces, when the pressure of the ice is equal to the external atmospheric air pressure.

Surface Tension: The tension which apparently exists in an interface between a liquid and a gas, a liquid and a solid, or a solid and a gas. Ascribed to the effects of attractive forces between the molecules at the interface, it is often referred to as interfacial tension, or interfacial energy. The latter term is also used synonymously with surface tension in the present volume.

INTRODUCTION

The susceptibility to frost heave or ice lensing of different soil types is an important criterion for pipeline location. This technical paper analyzes the susceptibility to frost heave of soils at selected sites along the Liard River Valley from the confluence of the Liard and the Mackenzie Rivers at Fort Simpson, to the confluence of the South Nahanni and Liard Rivers at Nahanni Butte. Soil samples were obtained at possible pipeline river crossing sites. The sampling sites are described using photos, N.T.S. maps, and surficial geology maps. Fluvial characteristics concerning ice-water flood level heights were also measured at these sites.

The soil's susceptibility to frost heave is determined by pore pressure measurements. An apparatus, developed and described by the author (Riddle, 1972), was used to measure the water suction in frost-heaving soils. The apparatus measures the soil pore water pressures at the penetrating frost line and permits precise control of soil surface sub-freezing temperatures, by using thermo-electric cooling. This soil pore water suction is the suction at which ice replaces water and spreads throughout the soil sample.

The relative merits of four sites for pipeline crossing on the basis of frost susceptibility of soil types, site situation and fluvial characteristics at that site, are discussed.

A conclusion, with regard to the future of pore pressure measurements in determining the frost susceptibility of different soil types, with specific reference to its usefulness for pipeline location, is reached.

FROST SUSCEPTIBILITY OF SOILS

General Discussion

During freezing, soil pore water pressures at the frost line decrease, resulting in water migration to the frost line, where it freezes causing a "frost heave". The greater the pressure decrease or suction generated in the soil pore during freezing, the greater will be the heaving tendency for that soil compared to other soils that produce smaller suctions, assuming that the soils are all relatively permeable and that a source of water exists to produce the heave. Because of this heaving effect, soils that display large suctions during freezing are generally unsuitable for foundation construction purposes, such as in highway, pipeline and building construction. Frost damage to roads is a direct result of what occurs when this water is "sucked" up to the near surface layers of a frost susceptible subgrade material during freezing, and subsequently causes major damage to the road during the spring thaw.

Soil Suction During Freezing

Williams (1968a, p. 92) states: "If the ice crystal is represented by a sphere of radius r, then the pressure difference between the two phases in the case of ice and water is given by:

$$P_i - P_w = \frac{2\sigma i_w}{r_c}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where P_i = pressure of ice (normally atmospheric)

P_w = pressure of water in the soil pore

σi_w = surface tension, ice to water

r_c = radius of ice-water interface. This is generally expressed as the radius of the largest continuous pore size opening.

This equation also applies with minor qualifications, to ice developing inside a capillary tube. In such a case, the ice is polycrystalline and may have a considerable length; the interface between the ice and remaining water is curved (due to surface tension), and when as is usually assumed, the contact angle with the walls of the tube is 0°, it has a radius approximately that of the tube.

A similar phenomenon is the rise of water up a capillary tube, which is the result of the lower pressure of the water immediately below the curved meniscus compared to that of the air above it. The pores of soils can be regarded as a series of interconnected capillaries, and give rise in freezing to effects of the kind described by equation (1)."

Characteristics of Heaving Ground

The degree of ice lensing and the resultant surface "heave" is generally a function of the soils, pore size, permeability and depth to the water table. The soil may be regarded as an open system, with the pressure of the pore water in that system continuing to decrease until equation (1) is satisfied. Ice lensing or frost lensing, will continue to occur as long as the pore water pressure at the frost line is less than the pore water pressure in the remaining soil pores. This results in water migration from the areas of higher pressure to that of lower pressure.

Active frost heave, which results in large and frequent ice lenses, generally occurs in a relatively permeable soil that has small continuous pore openings, i.e. silty sands, silts and clay silts as opposed to sands and clays. A slow rate of freezing, a high ground water level making water readily available for migration to the frost line, and a low overburden pressure which will not impede the effect of the heaving pressure, will assist in the formation of ice lenses.

Stated mathematically, ice lenses develop when

$$\frac{2\sigma i_w}{r_c} > P_i - P_w = \frac{2\sigma i_w}{r i_w}$$

where P_i, P_w and $2\sigma i_w/r_c$ refer to conditions at the frost line. The pressure in the ice P_i, is generally equal to the total pressure of the overburden γx, where γ = bulk density, x = depth. It may be slightly increased if expansion of the ice lens is resisted by the strength of the soil, but this increment of

pressure will be ignored.

SITE DESCRIPTIONS

Four potential crossing sites were studied in the vicinity of Martin Island (Site 1), the ferry crossing on the Liard River (Site 2), the Liard River slump (Site 3) and Swan Point, near Nahanni Butte (Site 4) (Fig. 1). The surficial geology at each site is described in Table 1. Photographs for each site are included in Appendix 1. An account of ice-water flood level height indicators along the Liard River (Henoch, 1972), gives some indication of the degree of flooding and ice jamming that may be expected at these sites under study.

SOURCES OF DATA (Field and Experimental)

Soil Sample

The soil samples were collected from the exposed cut banks, for both the Liard and Mackenzie River sites, at depths of 0.6 m and 1.2 m below the first terrace level. Photos of the cut banks, from where samples were taken are given in Appendix 1. Samples were collected manually and transported to the laboratory in plastic bags.

Experimental Data Sources

Soil pore water pressures during freezing (Riddle, 1972).

The soil suction is strictly represented by $P_i - P_w$, as shown in equation (1). P_i, under ideal conditions, would be equal to atmospheric pressure and therefore, would be neglected. However, in this particular experiment, P_i is essentially equal to the stress of the cooling unit resting on the soil particles and on the ice crystals. P_i is a constant value and is assumed to be the same in all of the freezing tests. Therefore, the soil suction is correctly represented with the addition of P_i to the measured P_w value which is negative, as shown mathematically in the equation

$$P_i - (P_w) = \frac{2\sigma_w}{r_c} .$$

Thermo-electric cooling (Williams, 1968b) is used to obtain precise temperature control of a plate which rests on top of the soil sample. With thermo-electric cooling, an electric current from an external source is applied to produce a difference in temperature between one set of junctions (one side of the module) and the other. This is called the Peltier effect. When the "hot" junctions are maintained at some convenient temperature by means means of an air or water-cooled heat sink, the temperature of the "cold" junctions (and of any reasonably sized object thermally connected to them), may be precisely controlled by varying the strength of the electric current. In other words, if a soil sample in contact with the cold side is initially at a higher temperature, it will cool to the controlled temperature.

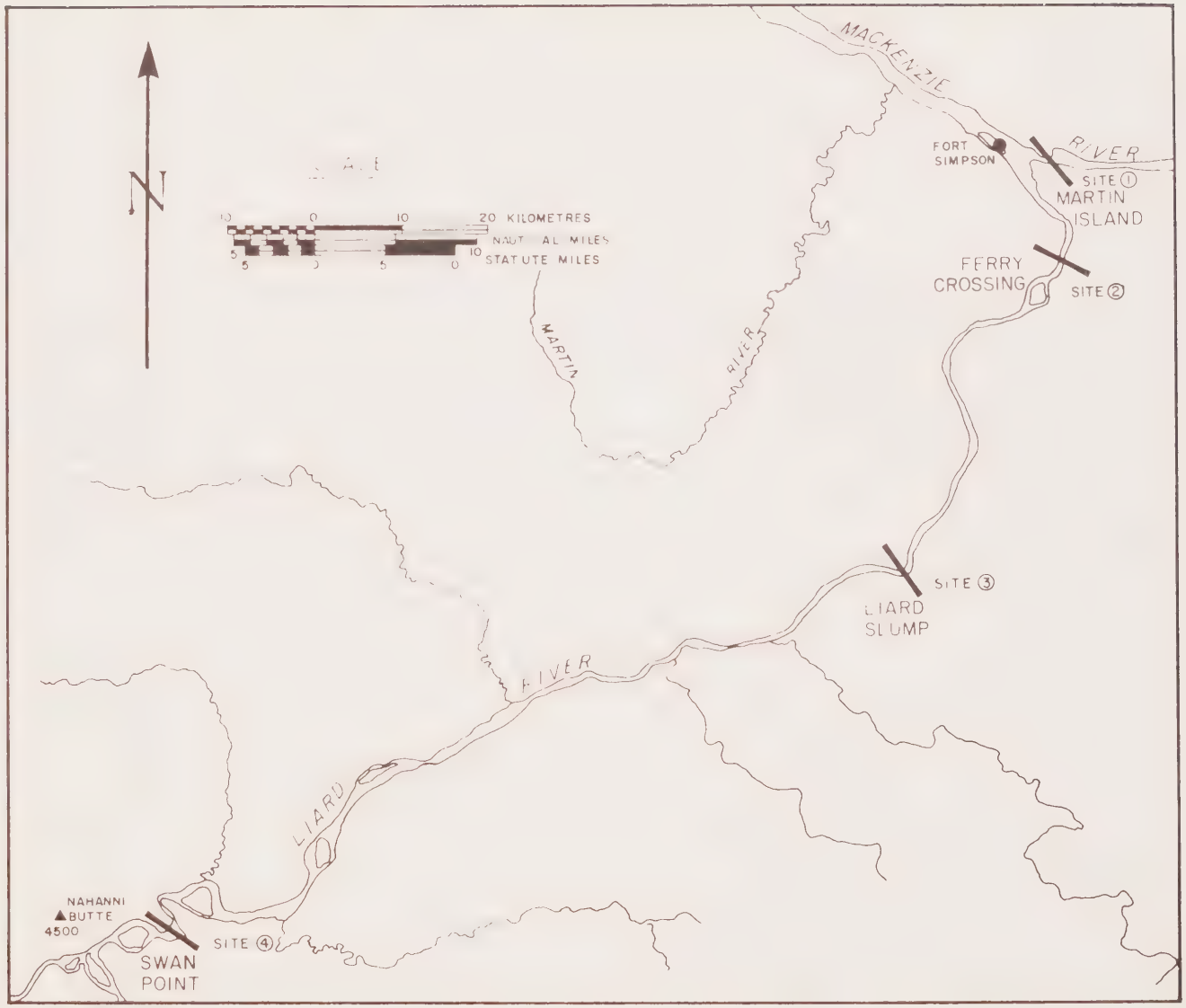
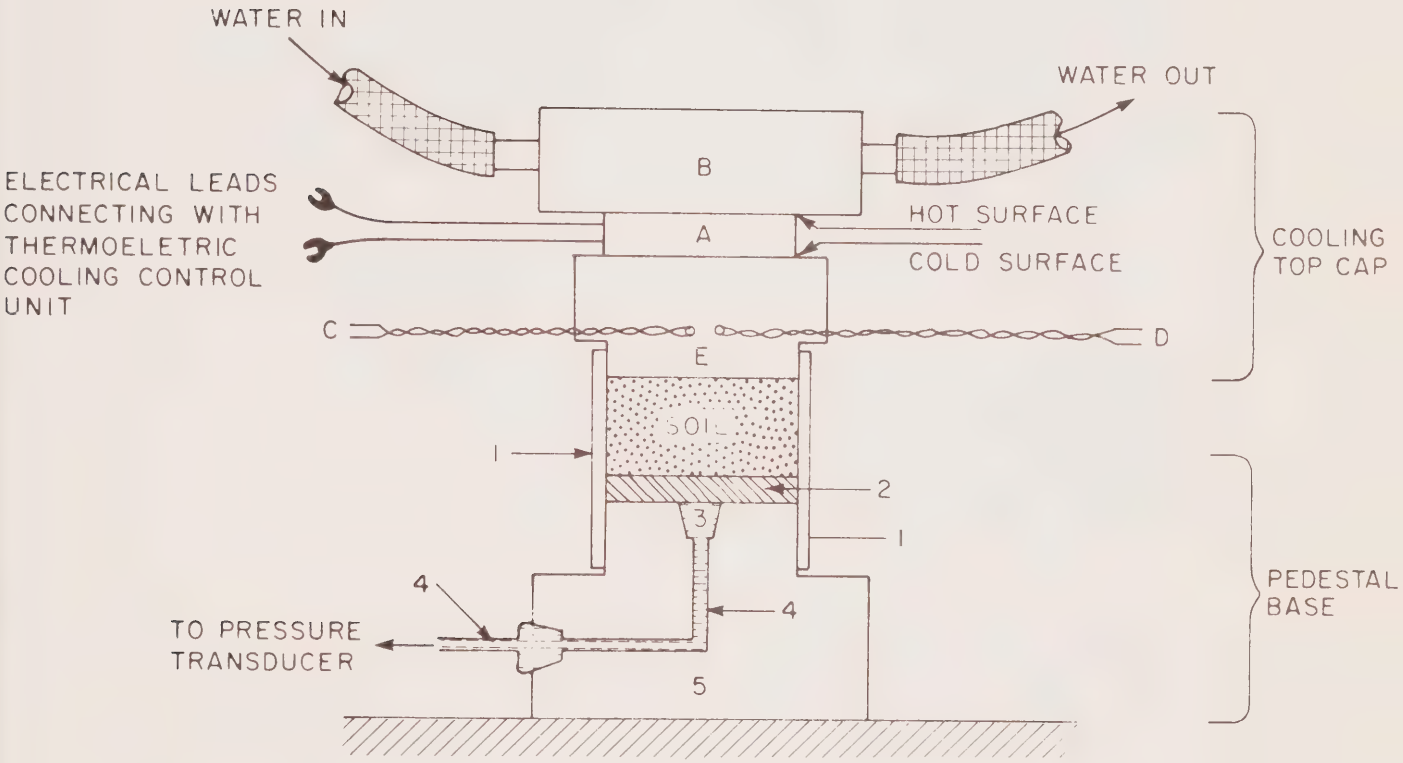


Figure 1. Map of study area, Mackenzie and Liard Rivers, Northwest Territories, 1:500,000.

The apparatus used in this experiment consists primarily of a rubber sheath and plexiglass base which respectively contain and support the soil specimen; a cooling top cap resting on the soil surface which freezes the sample; and a water channel in a plexiglass base connecting the soil to a pressure transducer which measures the soil suctions generated at the frost line during freezing (see diagram below). The suction is expressed as an equivalent water column in centimeters.



Legend

Cooling Top Cap

A Peltier Module

B Water Cooled Heat Sink

C Thermistor No. 1 (feedback sensor for thermoelectric cooling control unit

D Thermistor No. 2 (sensor to record top cap base plate temperature)

E Circular Top Cap Base Plate (rests on soil surface)

Pedestal Base

1 Circular Rubber Sheath (contains saturated soil specimen)

2 Porous Brass Filter Plate

3 Calibration Socket

4 Water filled Channel (Pressure differentials in soil transmitted via water column)

5 Plexiglass Base

(diagram after Williams)

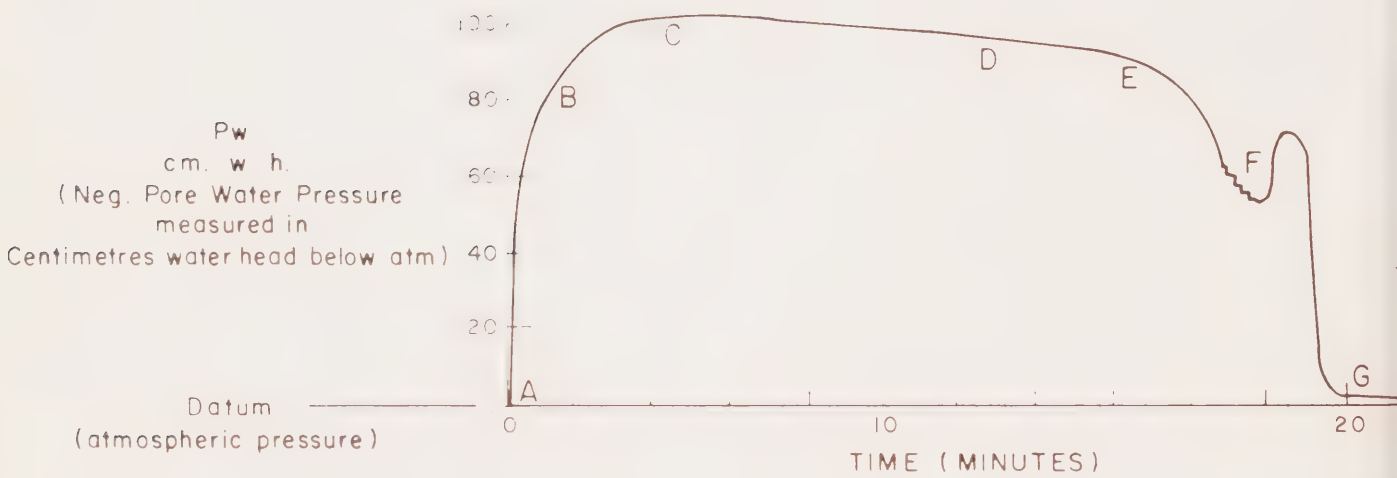
Data Analysis

The suctions generated at the frost line upon freezing a given soil specimen at a specific sub-freezing surface temperature are measured by a pressure transducer and recorded on a strip chart recorder, thereby producing a "suction vs time" curve for that soil at that applied sub-freezing surface temperature. The following illustrates the shape and the features that commonly occur on most suction vs time curves.

Typical "Suction vs Time"

For a Silty Sand Frozen at -5°C (cooling plate temp.)

(See also Figures 4 and 7 for typical curves)



Explanation of Features on "Suction vs Time"

(refer to letter on figure)

A - mechanically induced nucleation results in rapid ice growth of supercooled water which produces a small pressure increase and the liberation of heat (the latent heat of fusion).

B - frost line is just entering soil sample. The greater the impermeability of the soil, the greater the lag time for the suction to be felt by the transducer.

C - frost line has advanced about quarter way through the soil sample. The maximum suction plateau has been reached.

D - frost line has advanced about three-quarters through the soil specimen with a slight loss of suction being recorded. The reason is not yet clear, however, it may be caused by migrating fines (see figure 7).

E - sample completely frozen through and frost line now beginning to penetrate the large pores of the porous brass filter plate which produces a marked loss in suction in agreement with equation (1).

F - heating and the resultant thawing of the soil specimen is achieved by reversing the leads to the thermo-electric unit from the Peltier module, which initially produces an increase in suction, due to the volume decrease when changes to water.

G - complete thawing of the soil sample results in rapid loss in suction back to atmospheric pressure.

Soil Texture

The conventional grain size analysis test was used to determine the soil texture of the samples collected. Grain size distribution curves are included in Appendix 3.

Soil texture, although not as indicative of frost susceptibility as the more direct pore pressure measurements, is nevertheless included in this report to illustrate the textural class of soils that produce these suctions upon freezing.

RESULTS

Table 1. - SITE DESCRIPTION

See Figure 1 Site No.	Location	Geographical Co-ordinates	See Appendix 1 Photo Reference No.	Surficial Geology
1	N. shore Mackenzie opposite Martin Island - 8.2 m cut bank	61° 51' 30" 121° 17'	1	Bevelled Till Deposits (boulders, sand and gravel, silt and clay)
1	Martin Island - left bank	61° 51' 121° 15'	2	Bevelled Till Deposits (Boulders, sand and gravel, silt and clay)
1	S. shore Mackenzie opposite Martin Island	61° 50' 30" 121° 10'		Lacustrine Deposits (silt, silty clay, clayey silt stratified)
2	Ferry crossing, left (N-W) bank Liard River	61° 45' 121° 13'	3	Lake-Deltaic Deposits (stratified silty fine sand, fine sand, silt or clayey silt)
2	Ferry crossing, right (S-E) bank Liard River	61° 44' 121° 12'		High Terrace Deposits (silt cover with a sand and gravel bed)
3	Liard slump, right bank of river in rapids	61° 26' 121° 35'	4 7	Lacustrine Veneer over Moraine Deposits - mainly silt, clayey silt, and silty clay over till
3	Left bank Liard River opposite slump	61° 26' 121° 35'	5	Lake - Deltaic Deposits (sand, silt, clay silt over limestone bedrock)
4	Swan Point, left bank Liard River	61° 04' 30" 123° 10'	8	Floodplain Deposits - gravel and sand and some silt
4	Right bank Liard opposite Swan Point	61° 05' 123° 08'	6	Lake - Deltaic Deposits - (sand, silt and clayey silt)

Table 2 - FROST SUSCEPTIBILITY DATA

Sampling Depth 0.6 m

Site No.	Location	Avg. Soil suction Pi-Pw kgm/cm^2, see Appendix 3	Soil Texture - see Appendix 3 for Distribution Curves	Remarks
1	N. shore Mackenzie	0.66 (see Figure 2)	27% clay, 46% silt, 23% sand, 4% gravel, (see Figure 9)	very frost susceptible
1	Martin Island	0.61 (see Figure 3)	30% clay, 55% silt, 15% sand, (see Figure 10)	very frost susceptible
1	S. shore Mackenzie	0.59	28% clay, 68% silt, 4% sand (see Figure 10)	very frost susceptible
2	Ferry N.W. bank	0.50 (see Figure 5)	21% clay, 68% silt, 11% sand (see Figure 11)	very frost susceptible
2	Ferry S.E. bank	0.67	23% clay, 70% silt, 7% sand (see Figure 13)	very frost susceptible
3	Liard slump	0.15 (see Figure 7)	12% clay, 79% silt, 9% sand (see Figure 14)	slightly susceptible to frost heave
3	Left bank Liard opposite slump	-	-	bedrock (limestone) near surface
4	Swan Point	0.03	2% silt, 98% sand (see Figure 15)	neglible frost heave
4	Right bank Liard opposite Swan Point	0.47	18% clay, 78% silt, 4% sand (see Figure 16)	moderately frost susceptible

NOTE: 1 kgm/cm^2 = 1 atm. pressure
1,000 cm water head

Table 3. - FROST SUSCEPTIBILITY DATA

Sampling Depth 1.2 m

Site No.	Location	Avg. Soil suction $P_i - P_w$ kgm/cm^2, see Appendix 3	Soil Texture - see Appendix 3 for distribution curves	Remarks
1	N. shore Mackenzie	0.74	30% clay, 52% silt, 16% sand, 2% gravel (see figure 17)	very frost susceptible
1	Martin Island	0.61	22% clay, 57% silt, 17% sand, 4% gravel (see figure 18)	very frost susceptible
1	S. shore	0.96 (see figure 4)	36% clay, 63% silt, 1% sand (see figure 19)	very frost susceptible
2	Ferry N.W. bank	0.51	17% clay, 69% silt, 14% sand (see figure 20)	very frost susceptible
2	Ferry S.E. bank	0.32 (see figure 6)	15% clay, 71% silt, 14% sand (see figure 21)	moderately frost susceptible
3	Liard slump	0.55	21% clay, 34% silt, 33% sand, 12% gravel (see figure 22)	very frost susceptible
3	Left bank Liard opposite slump	-	-	bedrock (limestone) near surface
4	Swan Point	0.04	4% clay, 10% silt, 86% sand (see figure 23)	negligible frost heave
4	Right bank Liard opposite Swan Point	0.16 (see figure 8)	9% clay, 87% silt, 4% sand (see figure 24)	slightly susceptible to frost heave

NOTE: 1 kgm/cm = 1 atm. pressure
= 1,000 cm water head

DISCUSSION OF RESULTS

The results from this investigation give only a preliminary indication as to what may be expected with regard to frost susceptibility at the sites studied. Further investigation using a proper statistical sample at each site combined with the knowledge of the site's hydrology would give a more representative picture of the soil's stability to frost heave.

Nevertheless, analysis of the data reveals that from the point of view of soil frost susceptibility and flood and ice jamming susceptibility, the site which has the least number of drawbacks for a Liard River pipeline crossing would be in the vicinity of the Liard slump, in the rapids on solid bedrock.

The Mackenzie River crossing at Martin Island and the Liard River crossing at the Ferry both proved inadequate as pipeline crossing sites from the point of view of high susceptibility to frost in the clayey silt subsoils. These soils, with extended periods of extreme cold, experience large surface frost heave. This is caused by increased water migration to the frost line, as the frost line advances closer to the water table, resulting in large and frequent ice lenses. Additional factors of river width and ice jamming also rendered both sites unsatisfactory.

On account of the frost susceptibility of the silty subsoils on the right bank, Swan Point proved to be unsatisfactory for a pipeline crossing site.

CONCLUSION

Northern pipeline location is a compromise of many different factors. For the Liard River area, from the point of view of quantitative frost susceptibility criteria and obvious site and fluvial parameters, a location near the Liard slump would be the best for a pipeline river crossing site.

This paper has illustrated, using the Liard River Valley as its study area, the usefulness of quantitative frost susceptibility data determined by soil pore pressure measurements obtained during direct freezing tests. This testing procedure is much more efficient and considerably faster, minutes as compared to days, than the rather indirect method of determining frost susceptibility of a soil by grain size analysis. With further frozen ground research and investigation, especially with regard to arctic and sub-arctic pipeline location and construction, the potential of soil pore pressure measurement during freezing may be fully recognized.

ACKNOWLEDGEMENTS

I am indebted to Mr. W.E.S. Henoch in so many ways for if it had not been for him, this paper would not have been possible. I would also like to give special thanks to Marion Parker, Jerome Chyurlia and Ted Trindel who, at times, assisted me with the collecting of soil samples.

I am grateful to Dr. Williams at Carleton University, who allowed me the use of the Geography Department's Laboratory facilities, for the testing of the soil samples. I appreciate the time spent by Lyn Arsenault, Gerry Holdsworth and W.E.S. Henoch, who critically reviewed this paper before publication.

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APPENDIX 1

Photographs of soil sample sites



Photo 1. North shore of the Mackenzie River opposite Martin Island, site 1 .



Photo 2. Martin Island, site 1 frost susceptibility soil samples taken from "X".



Photo 9. Taken from Nahanni Butte, showing Liard River valley, upper left, with Swan Point marked by an arrow (site 4).



Photo 10. Liard River rapids with slump on right bank and limestone cliff on the left (site 3).

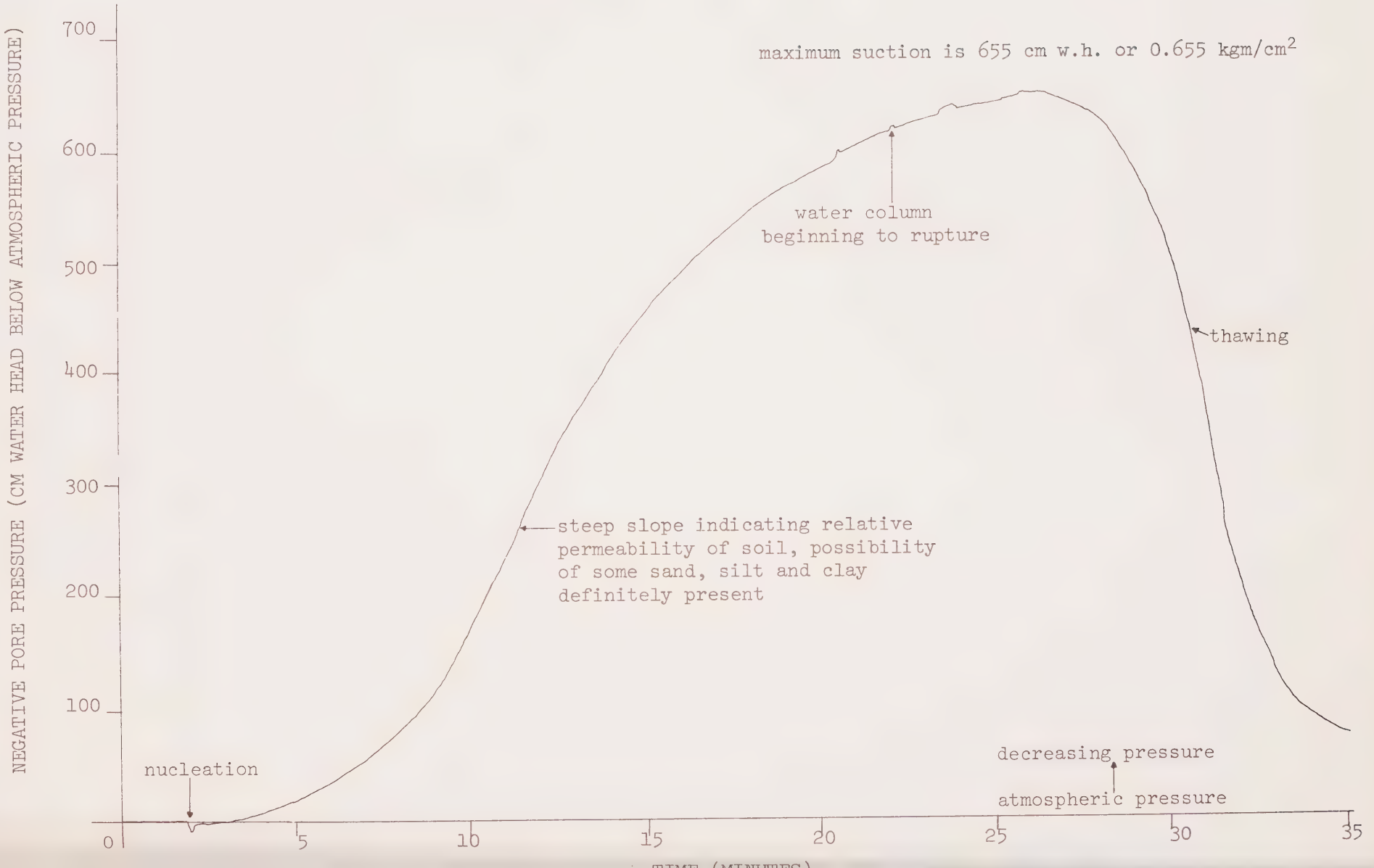
APPENDIX 2

Selected frost susceptibility curves

(Negative pore water pressure against time)

Figure 2

Site 1 North shore of Mackenzie River, adjacent to Martin Island.
Soil sample from 0.61 m depth, soil frozen at -5°C.



Site 1 Martin Island, left bank.
Soil sample from 0.61 m depth, soil frozen at -5°C.

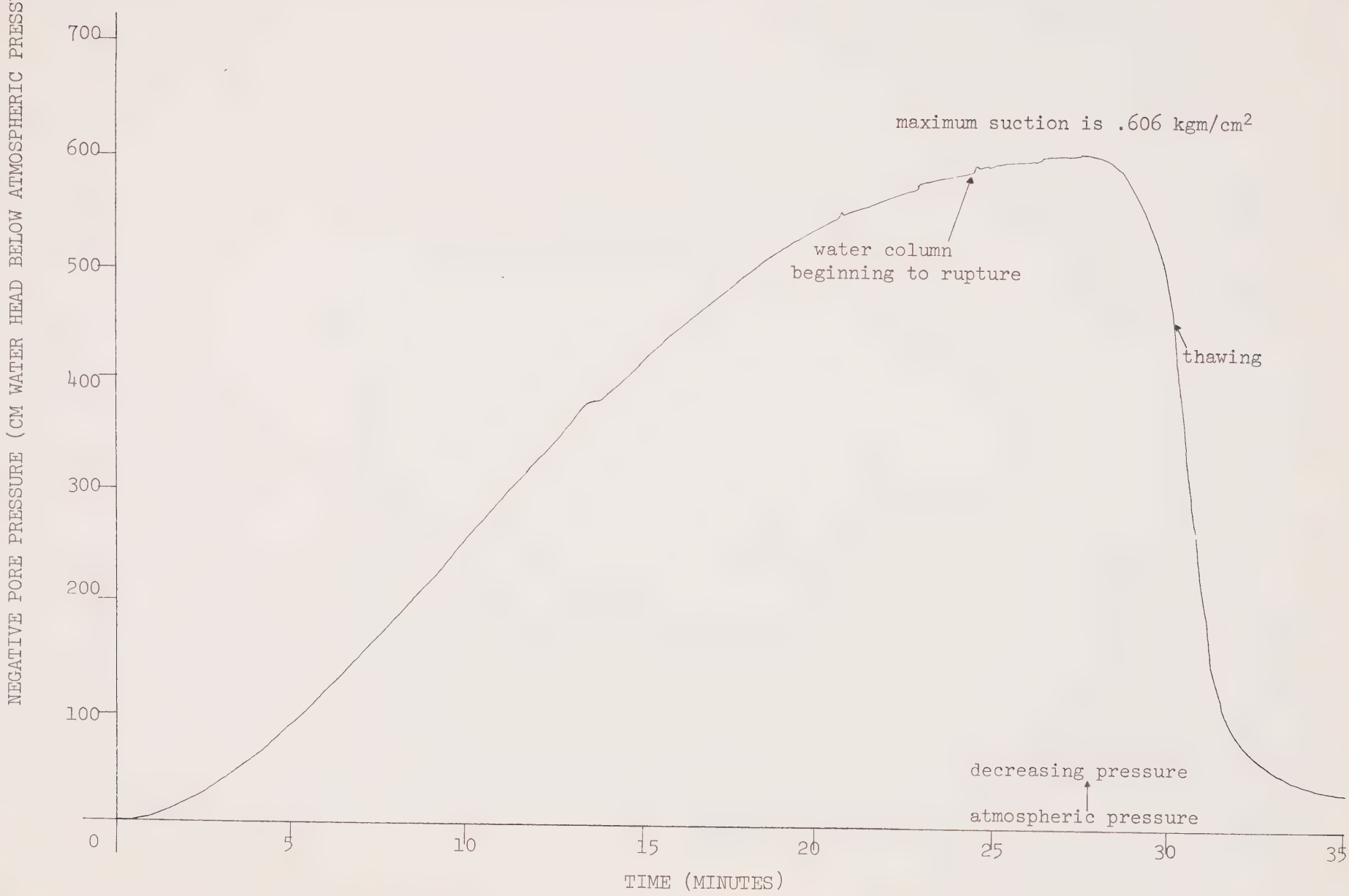


Figure 4

Site 1 South shore of Mackenzie River adjacent to Martin Island.
Soil sample from 1.22 m depth, frozen at -5°C.

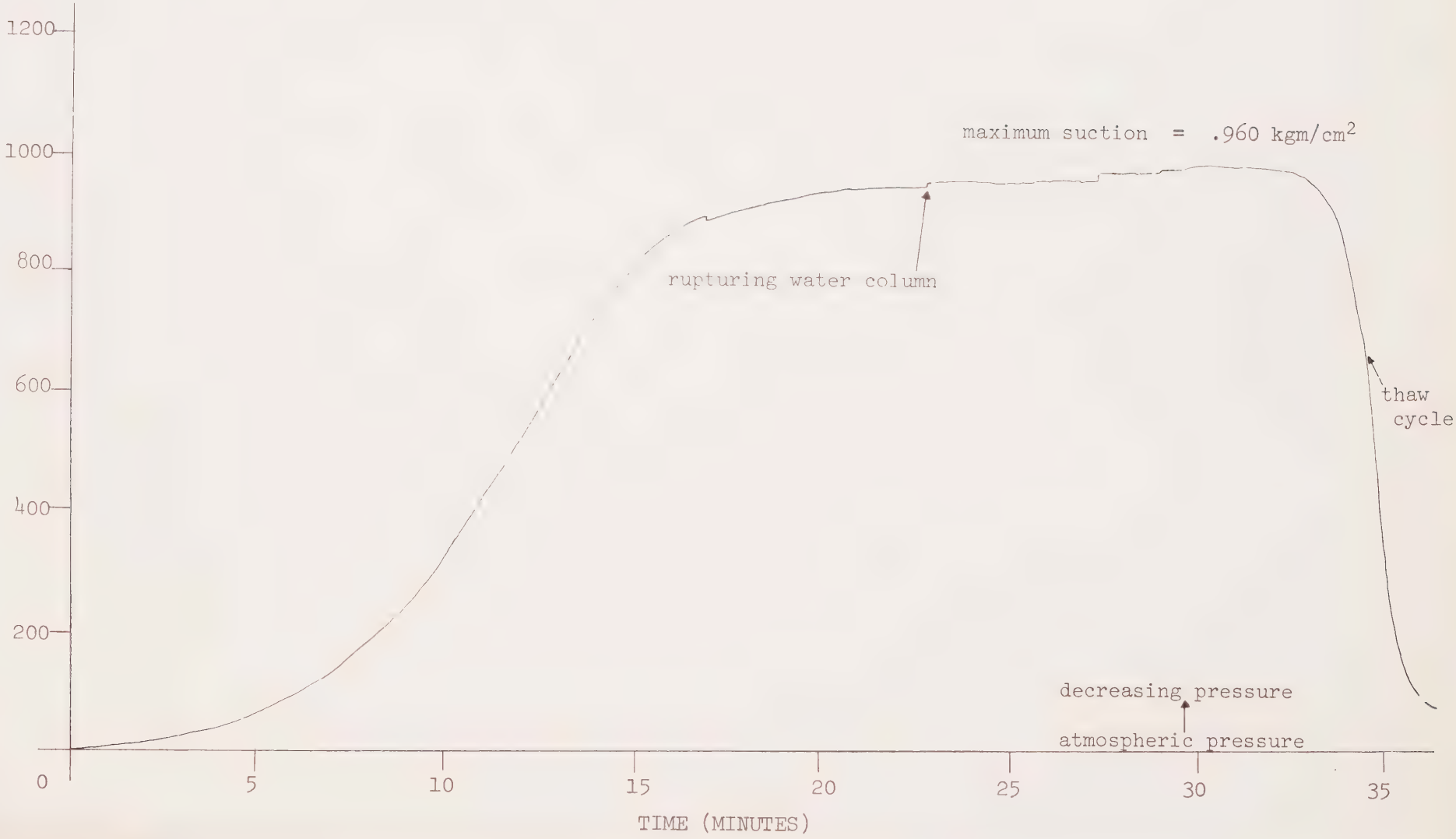


Figure 5

Site 2 Ferry crossing, left (NW) bank Liard River.
Soil sample from 0.61 in depth, soil frozen at -5°C.

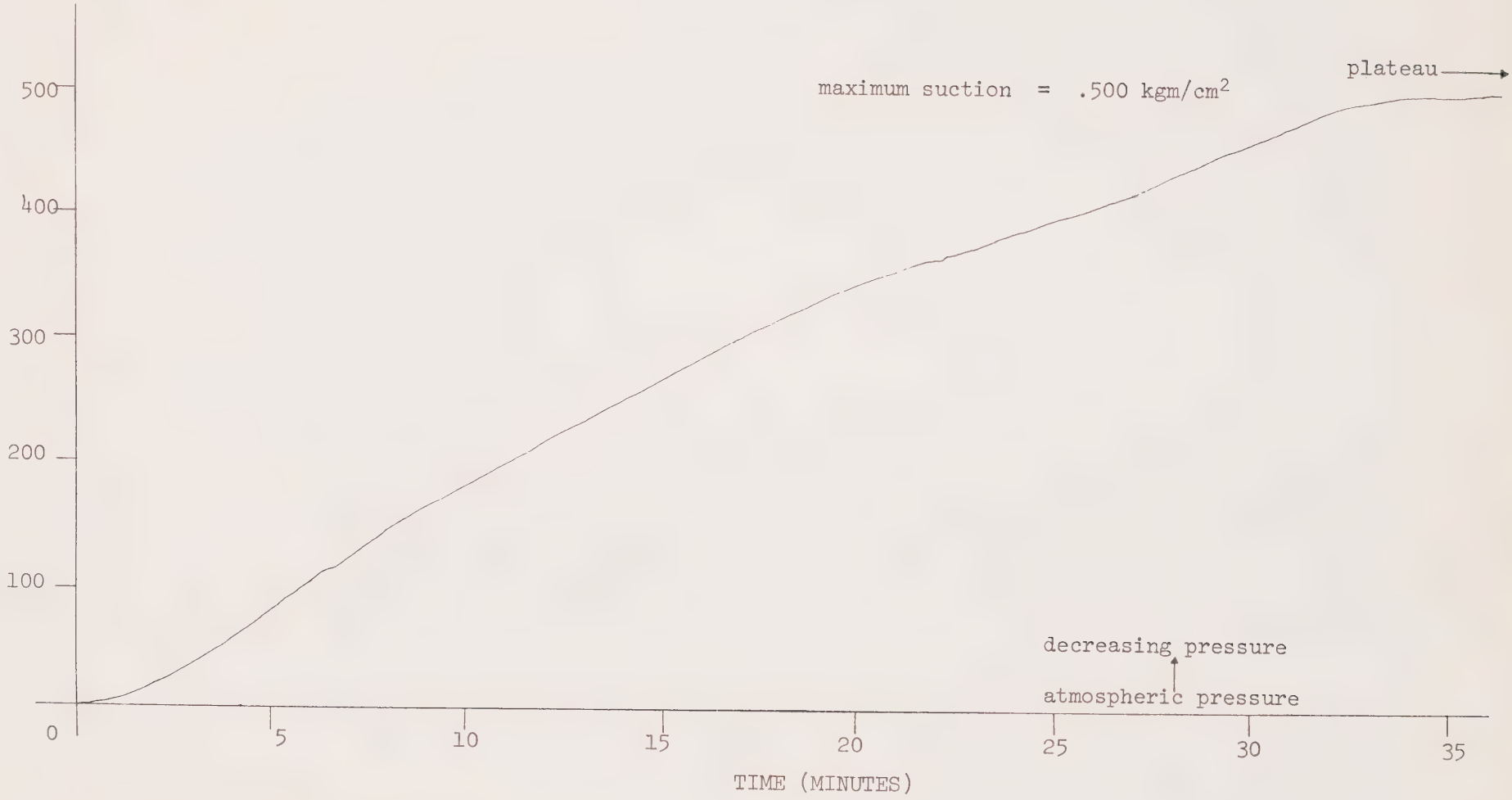


Figure 6

Site 2 Ferry crossing, right (SE) bank Liard River.
Soil sample from 1.22 m depth, soil frozen at -5°C.

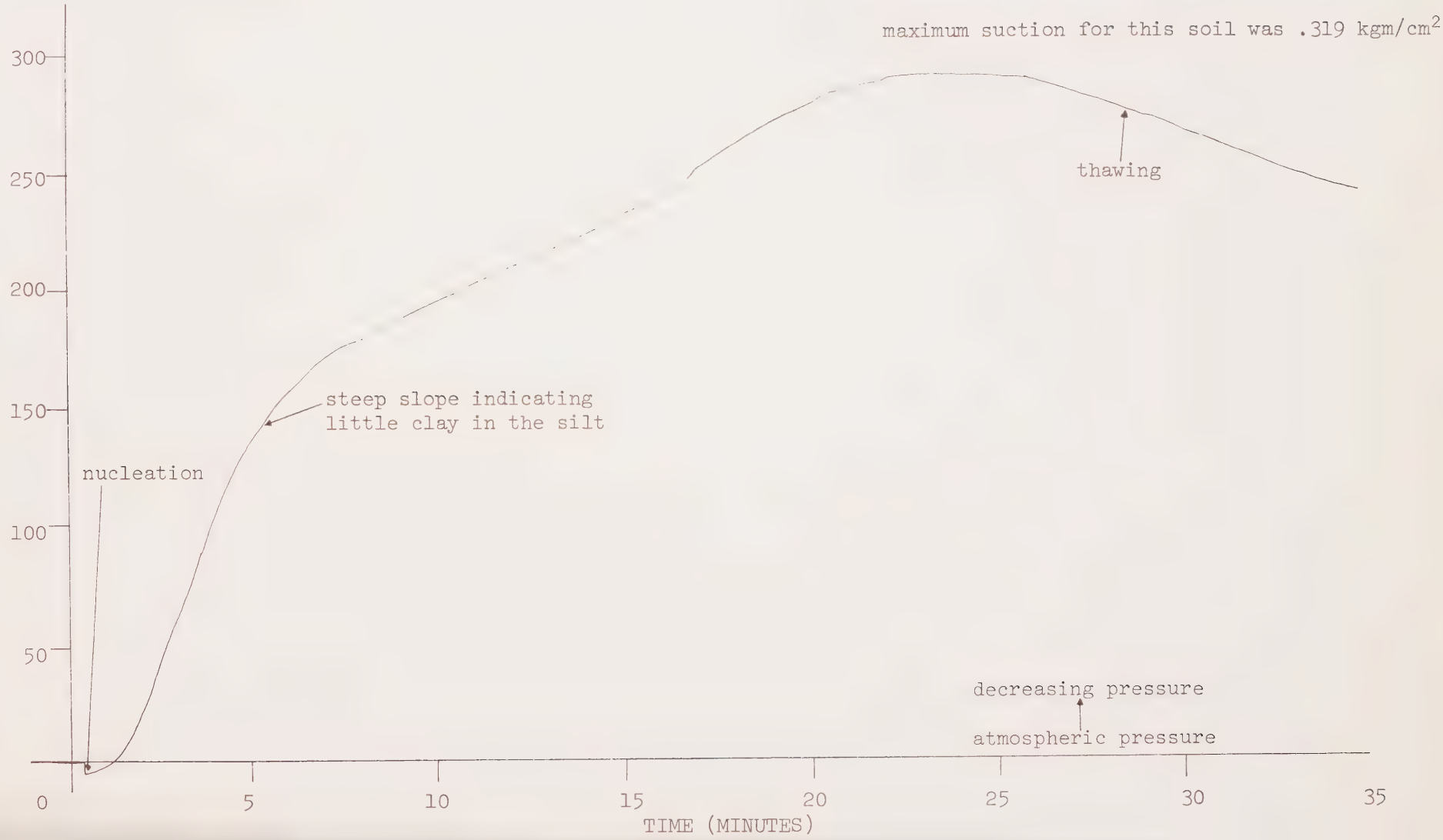


Figure 7

Site 3 Liard Slump, right bank Liard River.
Soil sample from 0.61 m depth, soil frozen at -5°C.

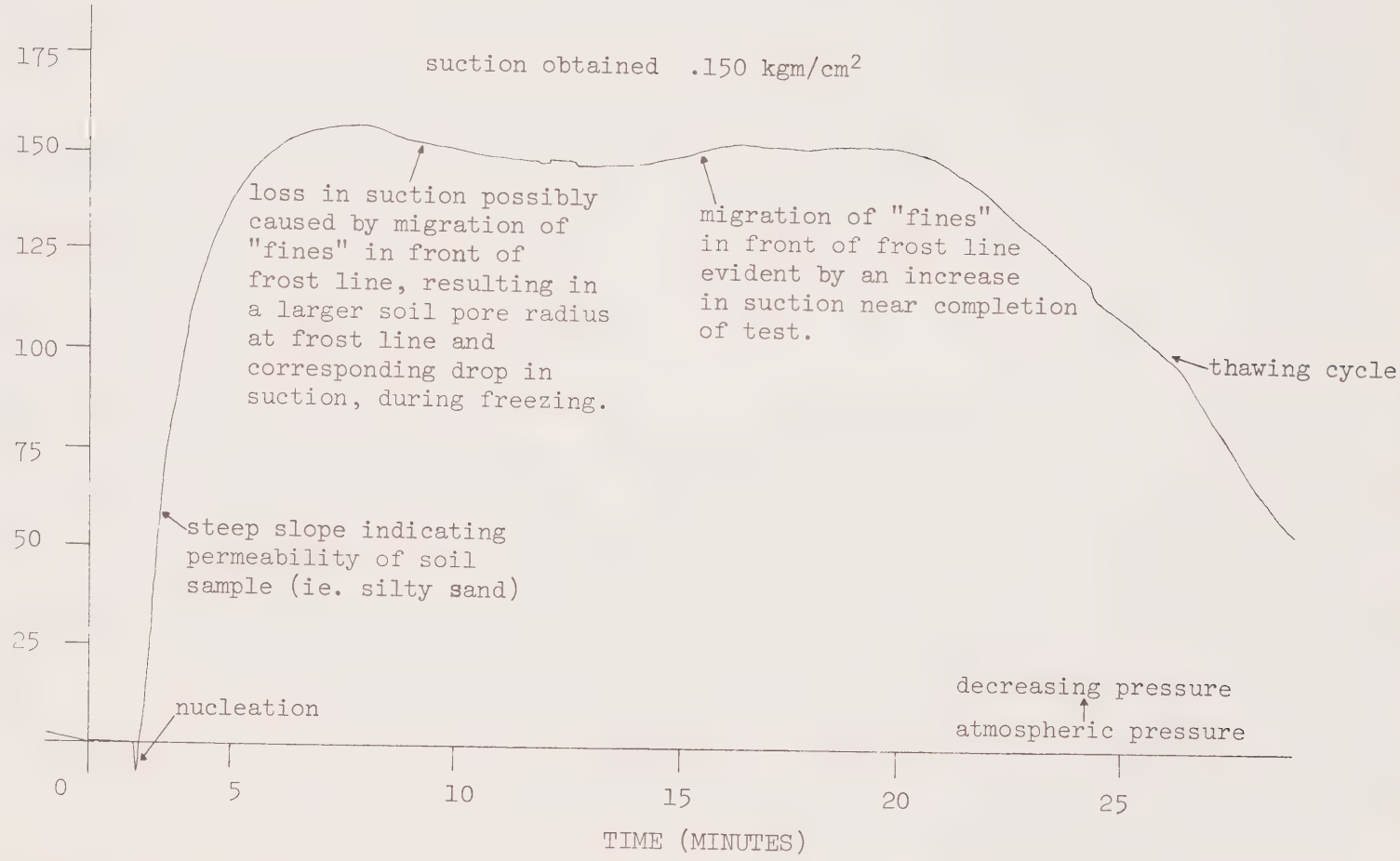
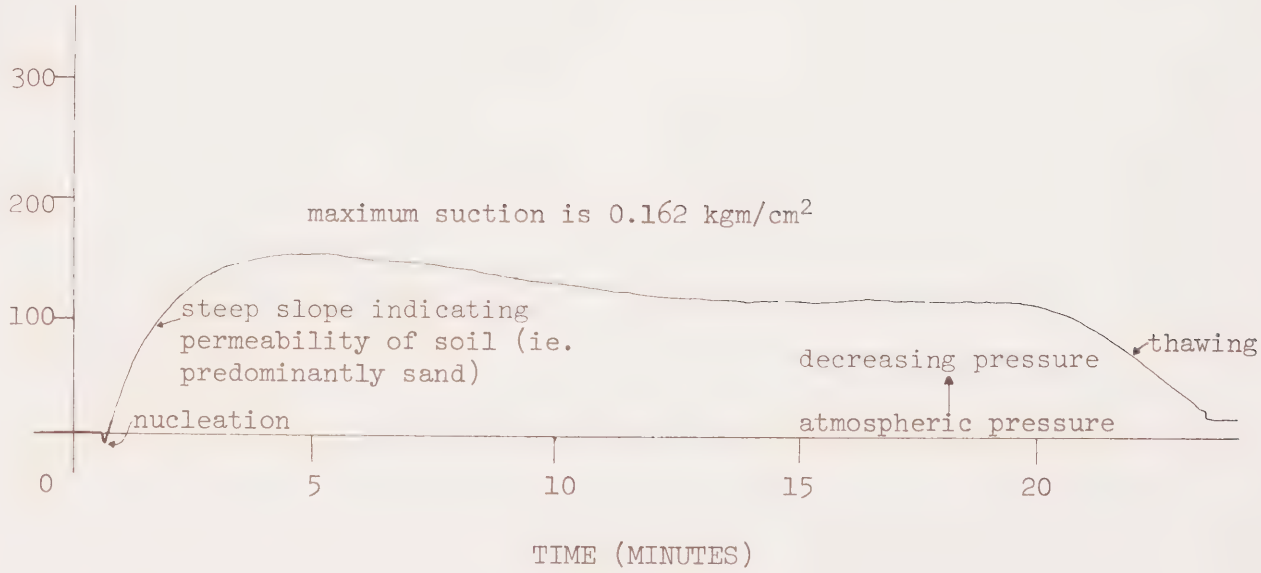


Figure 8

Site 4 Right bank of Liard River opposite Swan Point
Soil sample from 1.22 m depth, soil frozen at -5°C.



APPENDIX 3

Grain size distribution curves

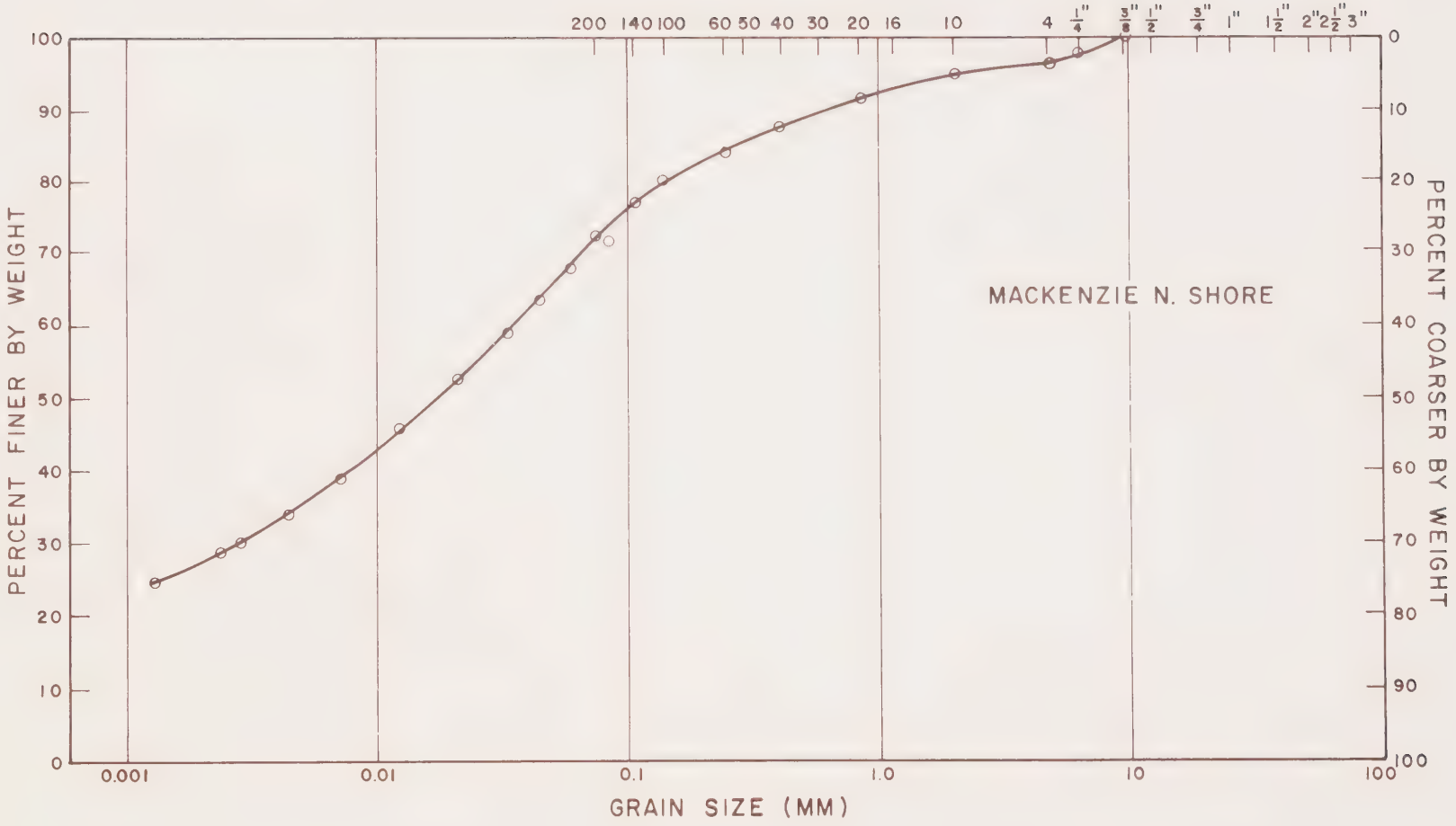


Figure 9. Grain size distribution of soil sample from 0.6 m depth, north shore of Mackenzie River, Site 1.

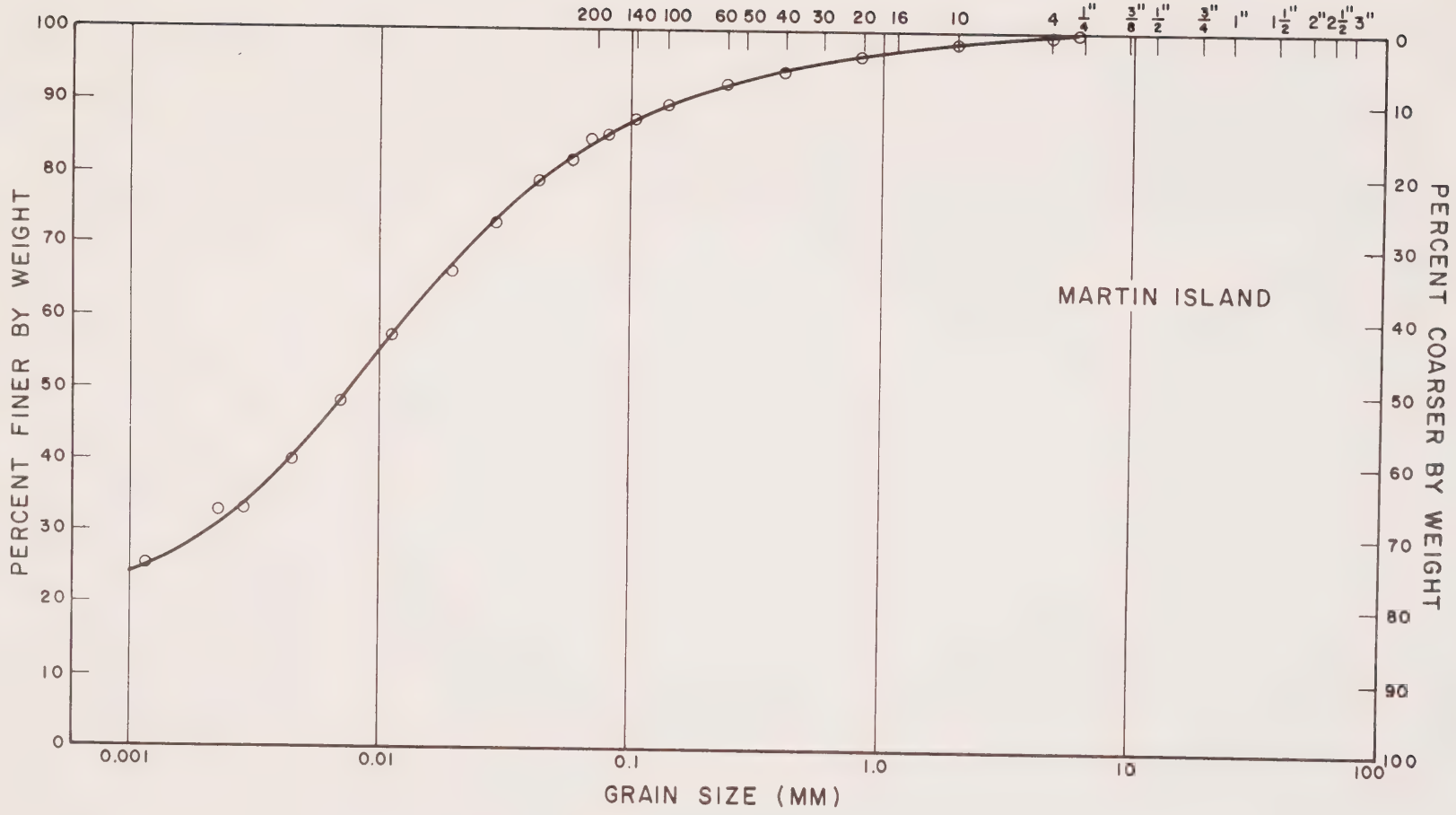


Figure 10. Grain size distribution of soil sample from 0.6 m depth, Martin Island, Site 1.

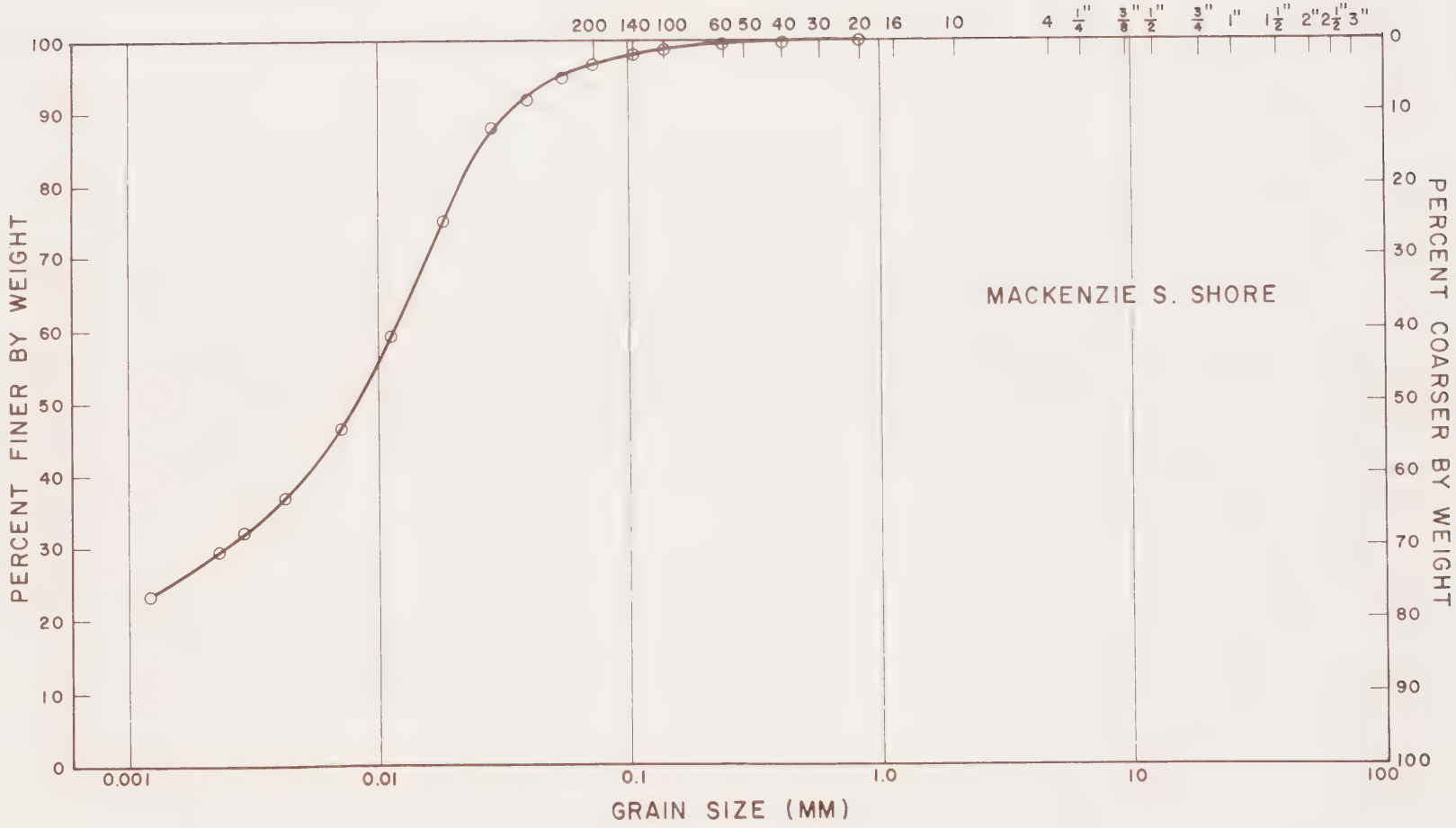


Figure 11. Grain size distribution of soil sample from 0.6 m depth, south shore of Mackenzie River, Site 1.

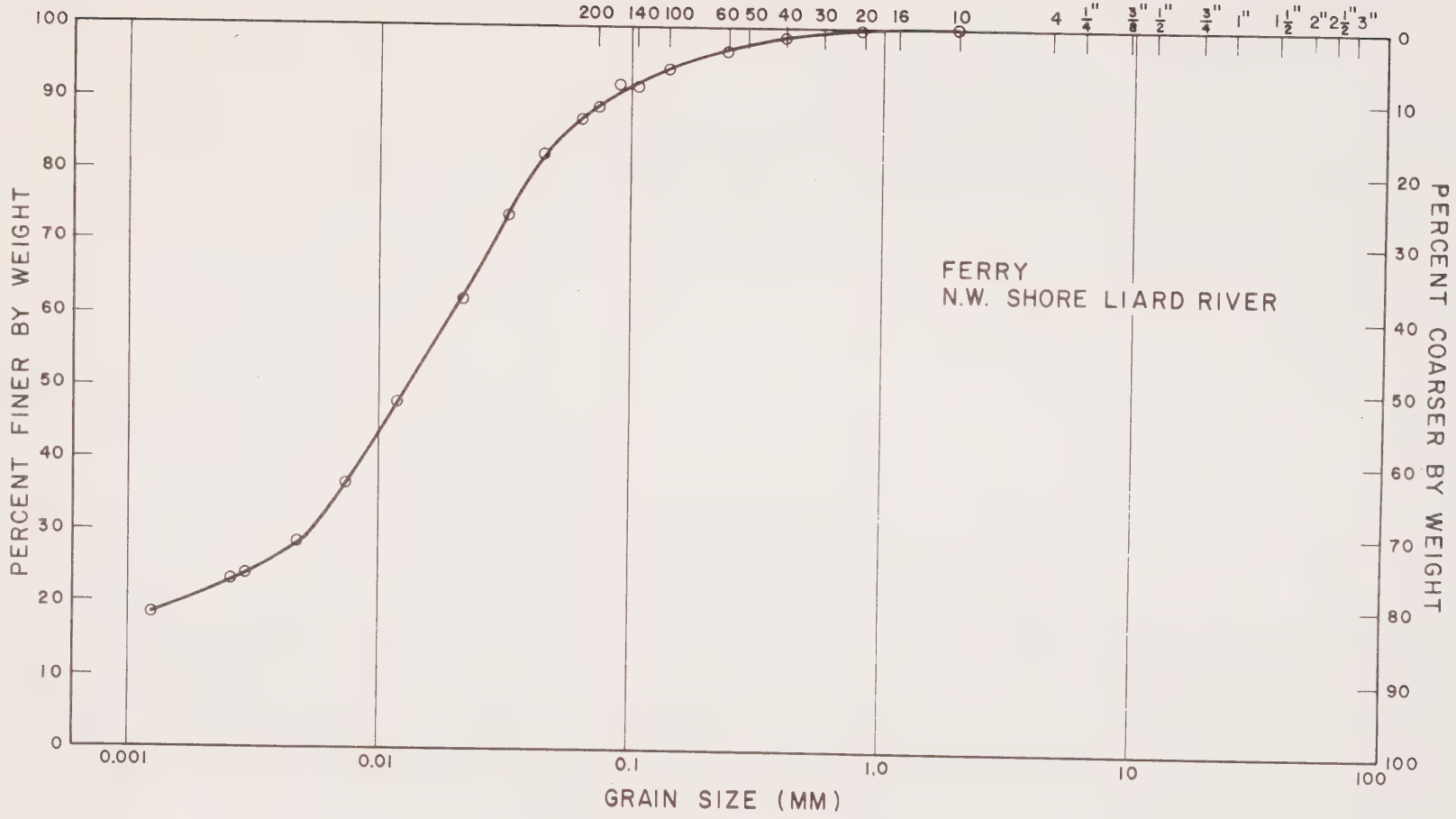


Figure 12. Grain size distribution of soil sample from 0.6 m depth, Ferry Crossing, north west bank of Liard River, Site 2.

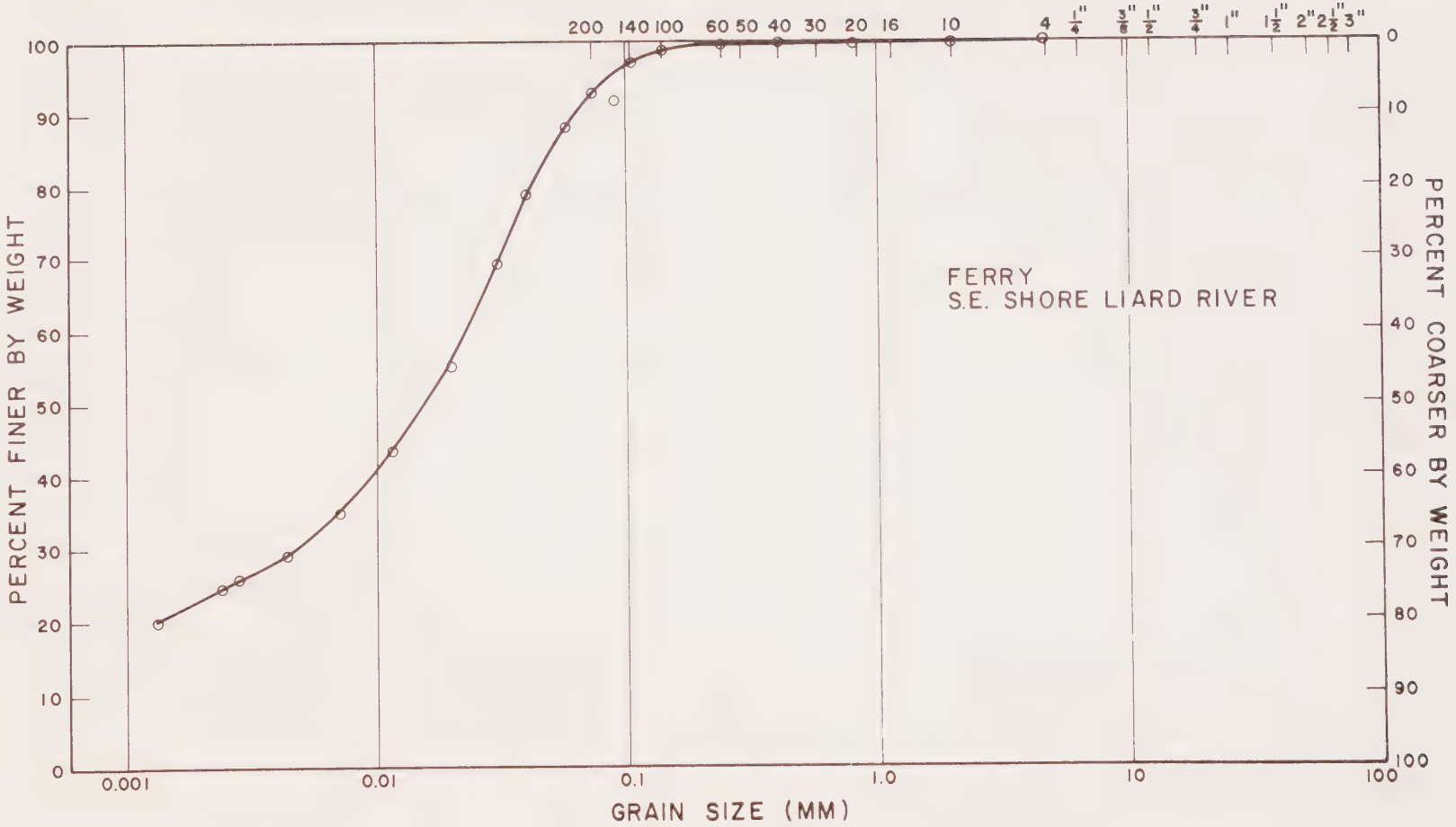


Figure 13. Grain size distribution of soil sample from 0.6 m depth, Ferry Crossing, south east bank of Liard River, Site 2.

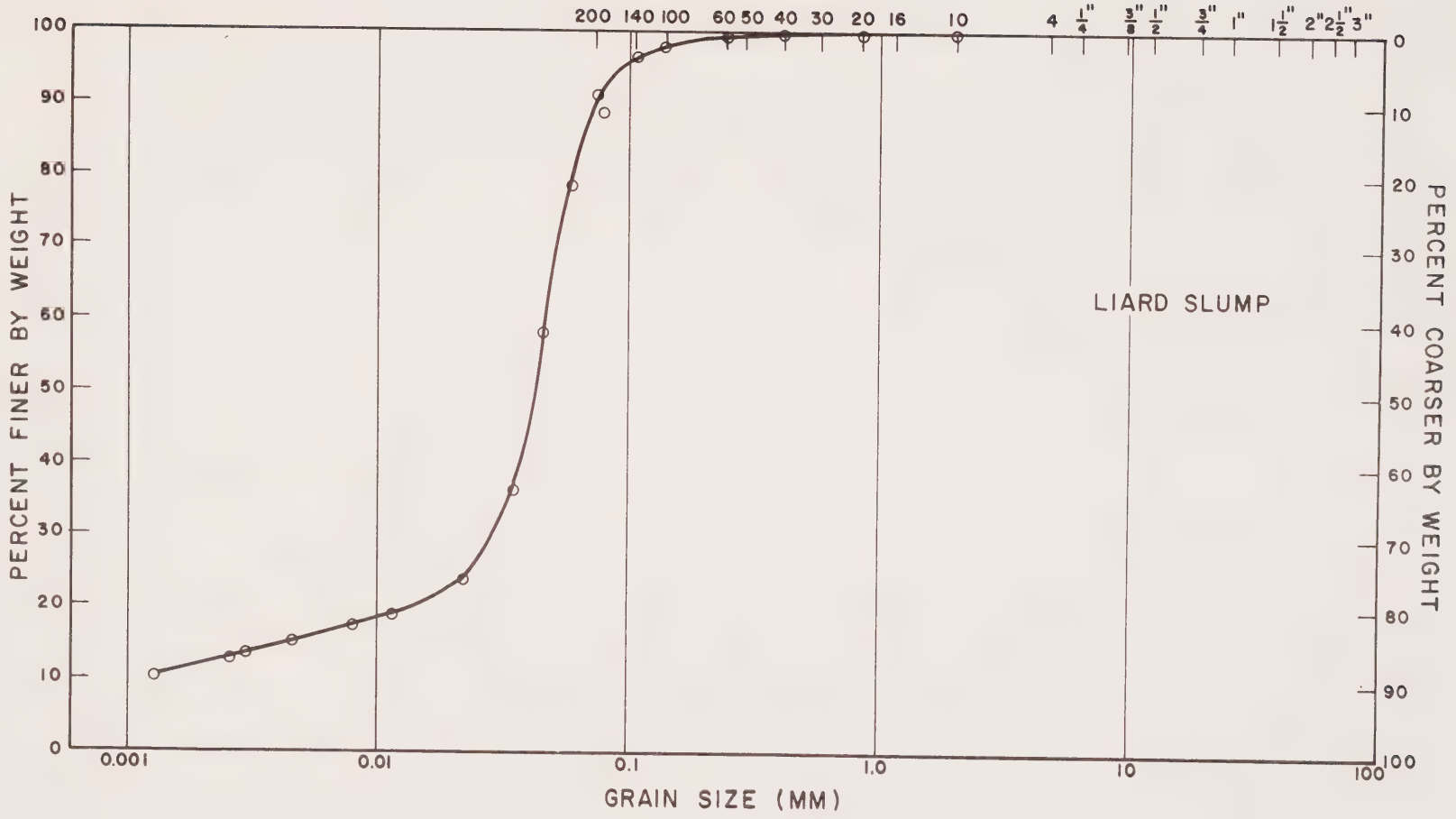


Figure 14. Grain size distribution of soil sample from 0.6 m depth, Liard Slump, Site 3.

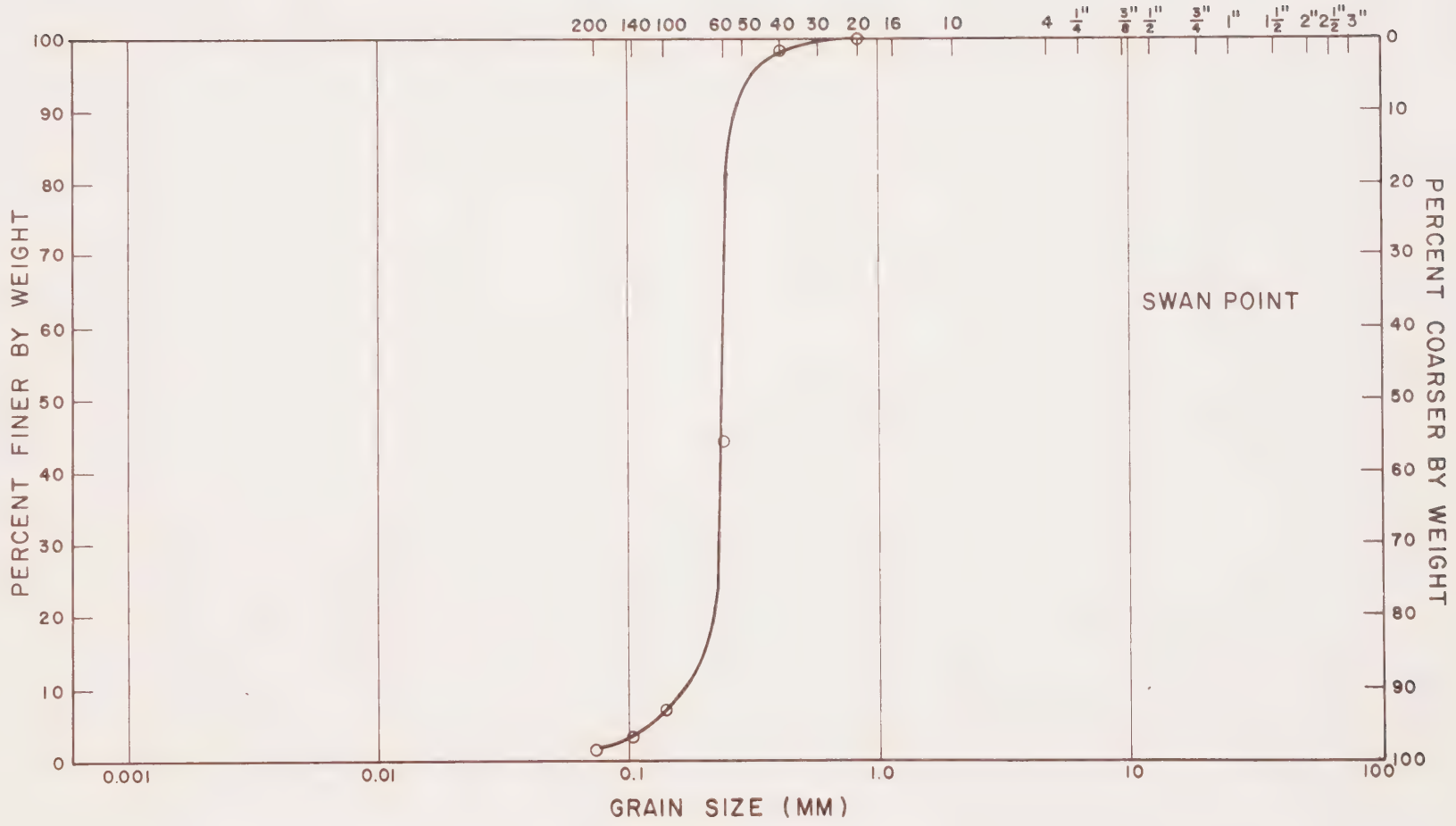


Figure 15. Grain size distribution of soil sample from 0.6 m depth, Swan Point, north bank of Liard River, Site 4.

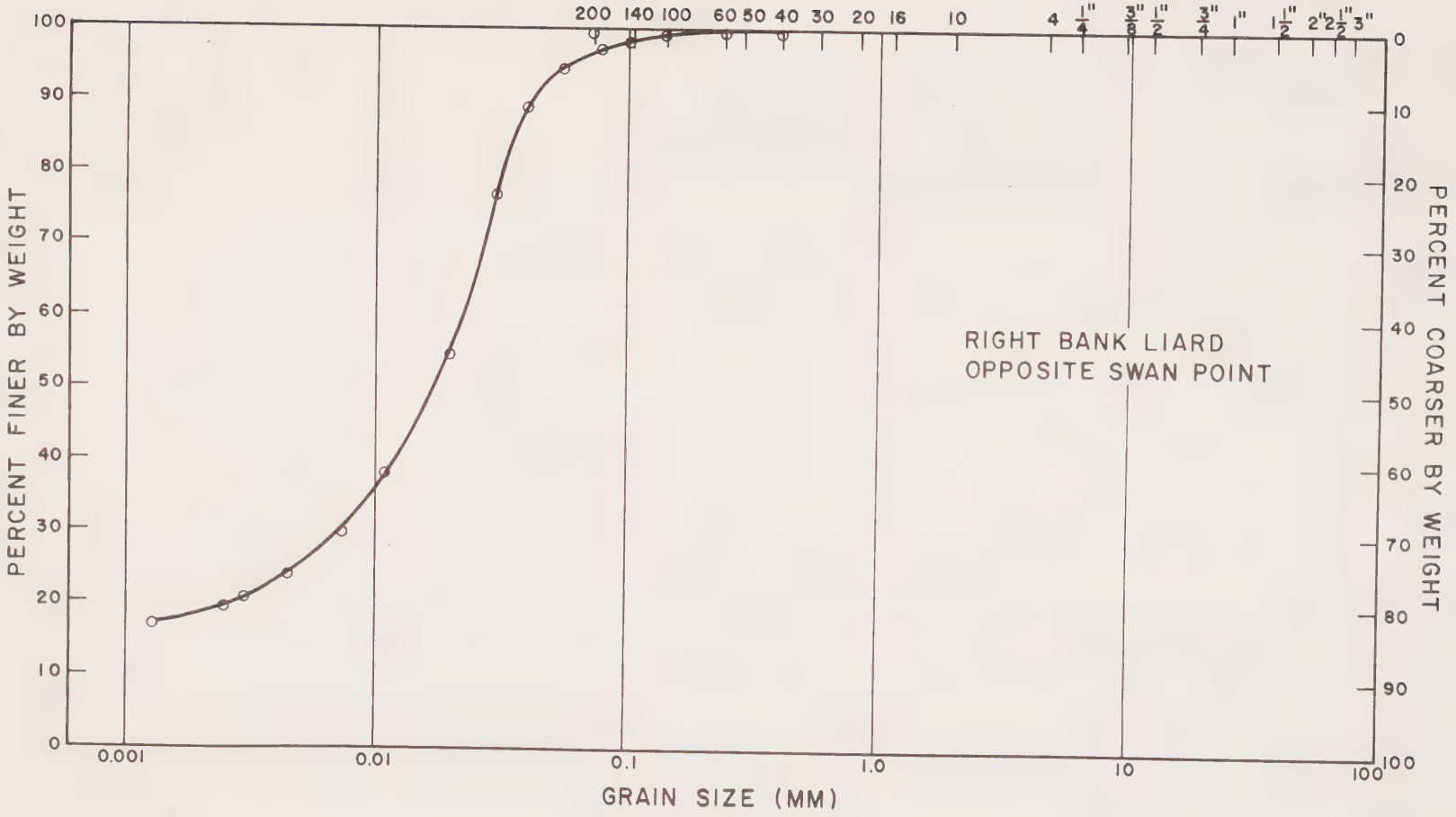


Figure 16. Grain size distribution of soil sample from 0.6 m depth, south bank of Liard River opposite Swan Point, Site 4.

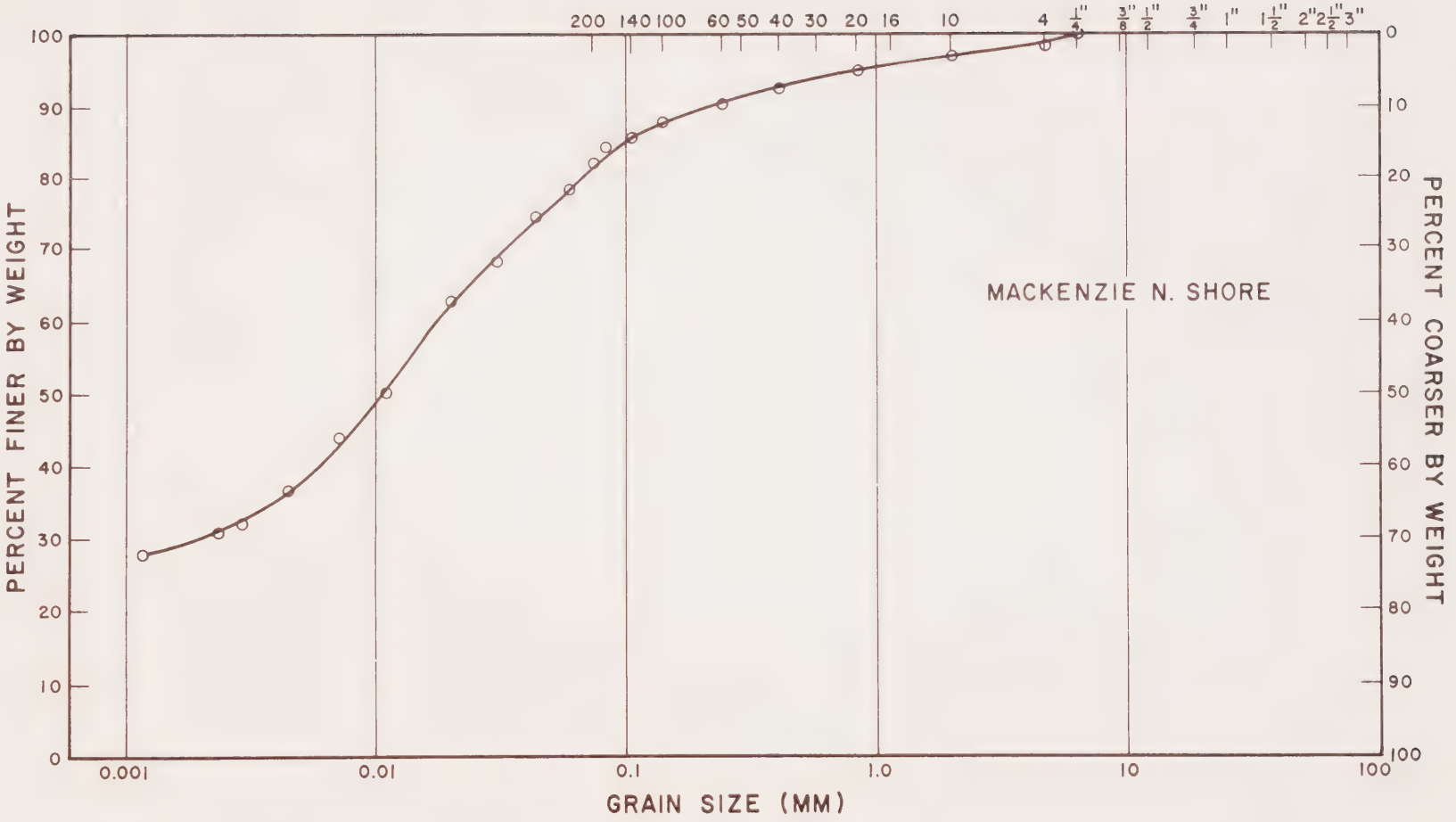


Figure 17. Grain size distribution of soil sample from 1.2 m depth, north shore of Mackenzie River, Site 1.

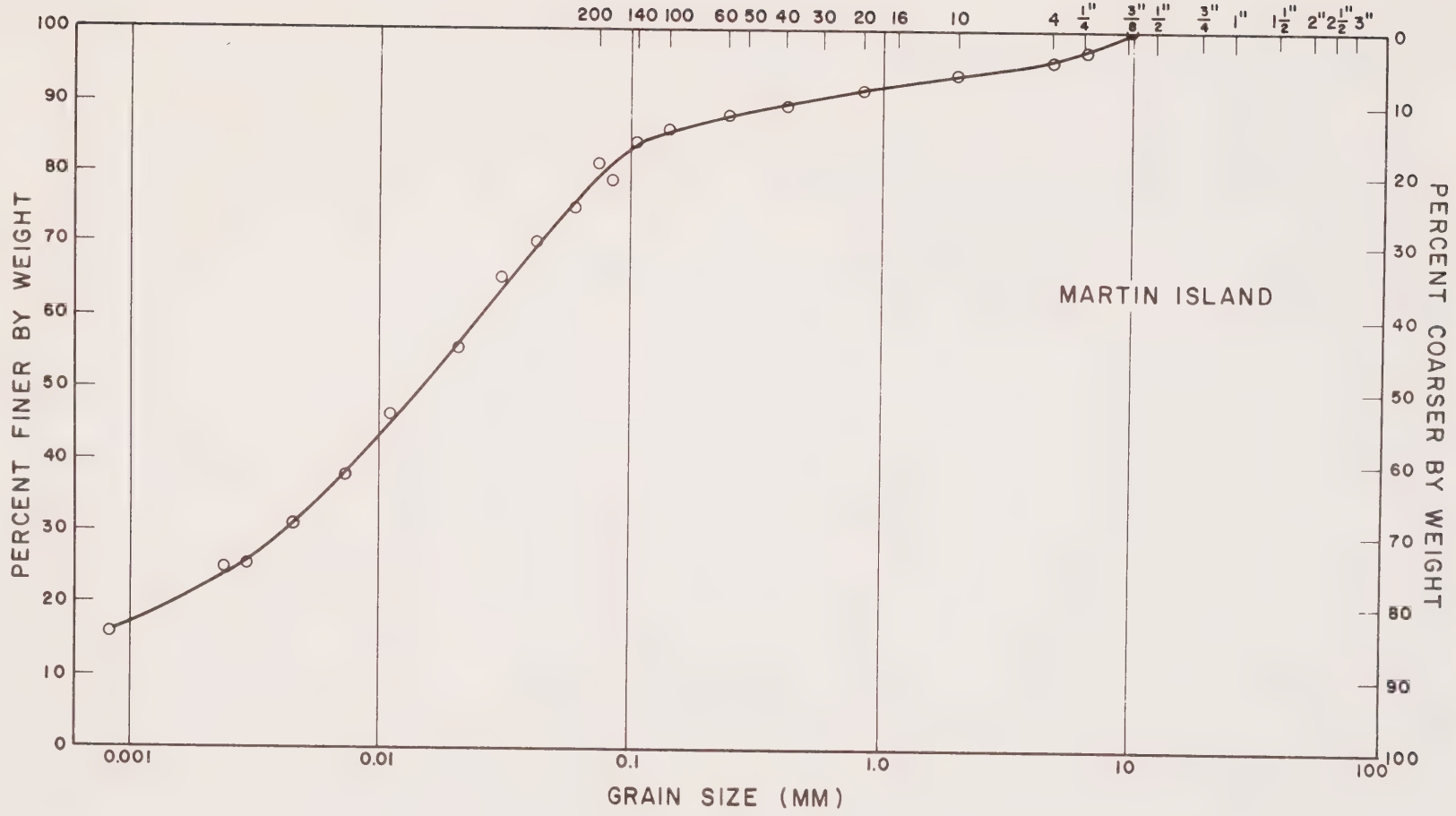


Figure 18. Grain size distribution of soil sample from 1.2 m depth, Martin Island, Site 1.

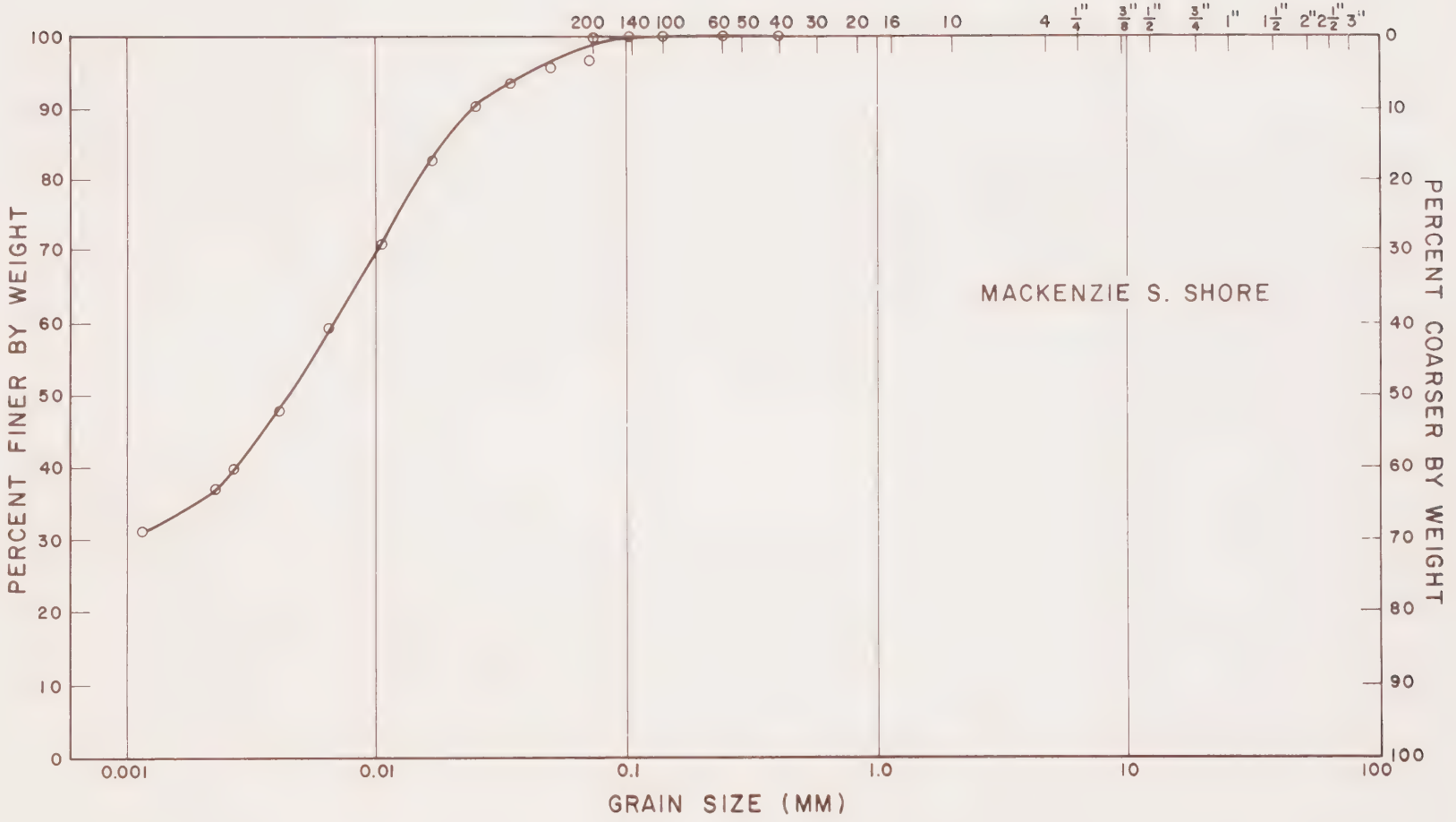


Figure 19. Grain size distribution of soil sample from 1.2 m depth, south shore of Mackenzie River, Site 1.

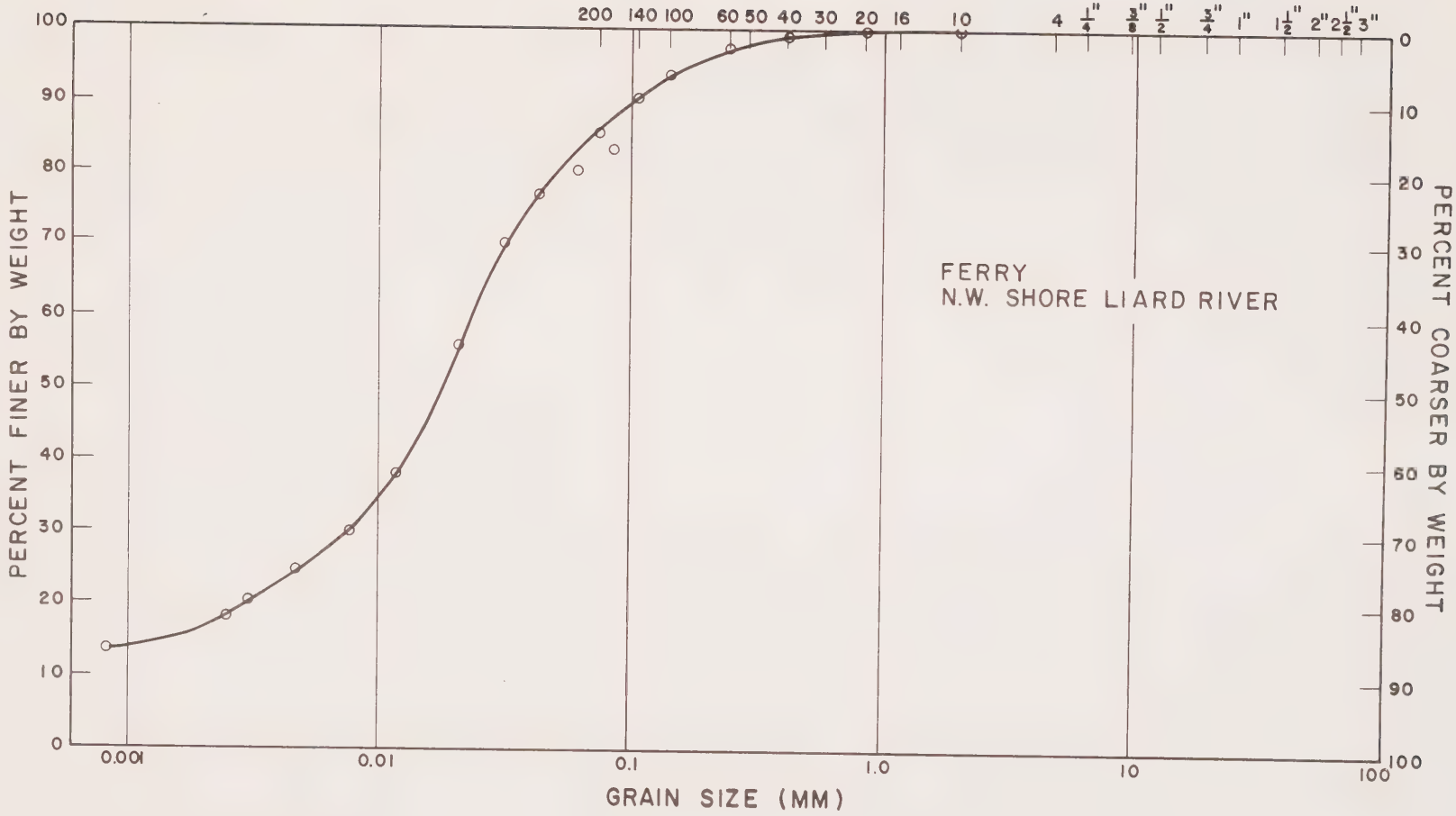


Figure 20. Grain size distribution of soil sample from 1.2 m depth, Ferry Crossing, north west bank of Liard River, Site 2.

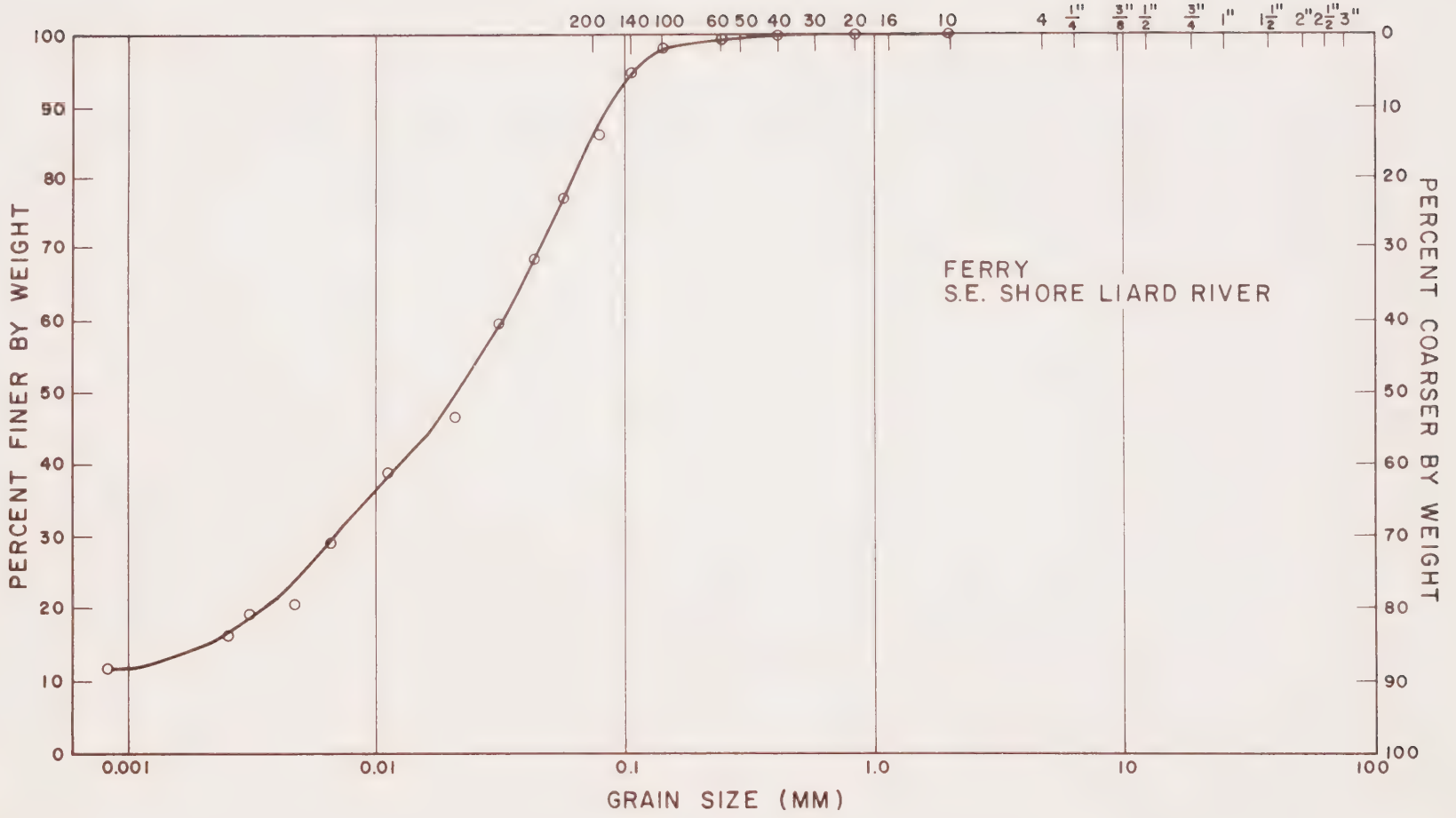


Figure 21. Grain size distribution of soil sample from 1.2 m depth, Ferry Crossing, south east bank of Liard River, Site 2.

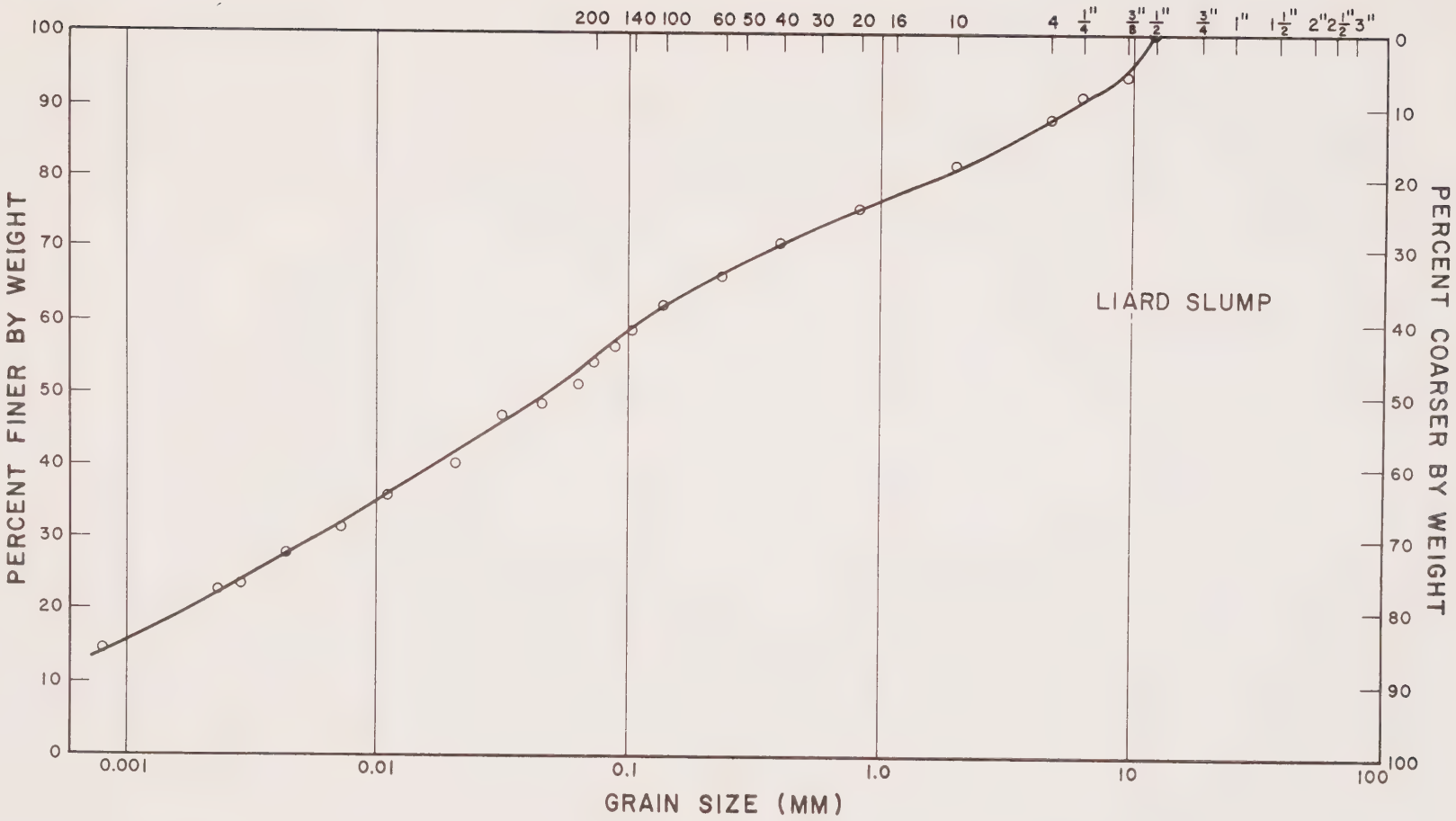


Figure 22. Grain size distribution of soil sample from 1.2 m depth, Liard Slump, Site 3.

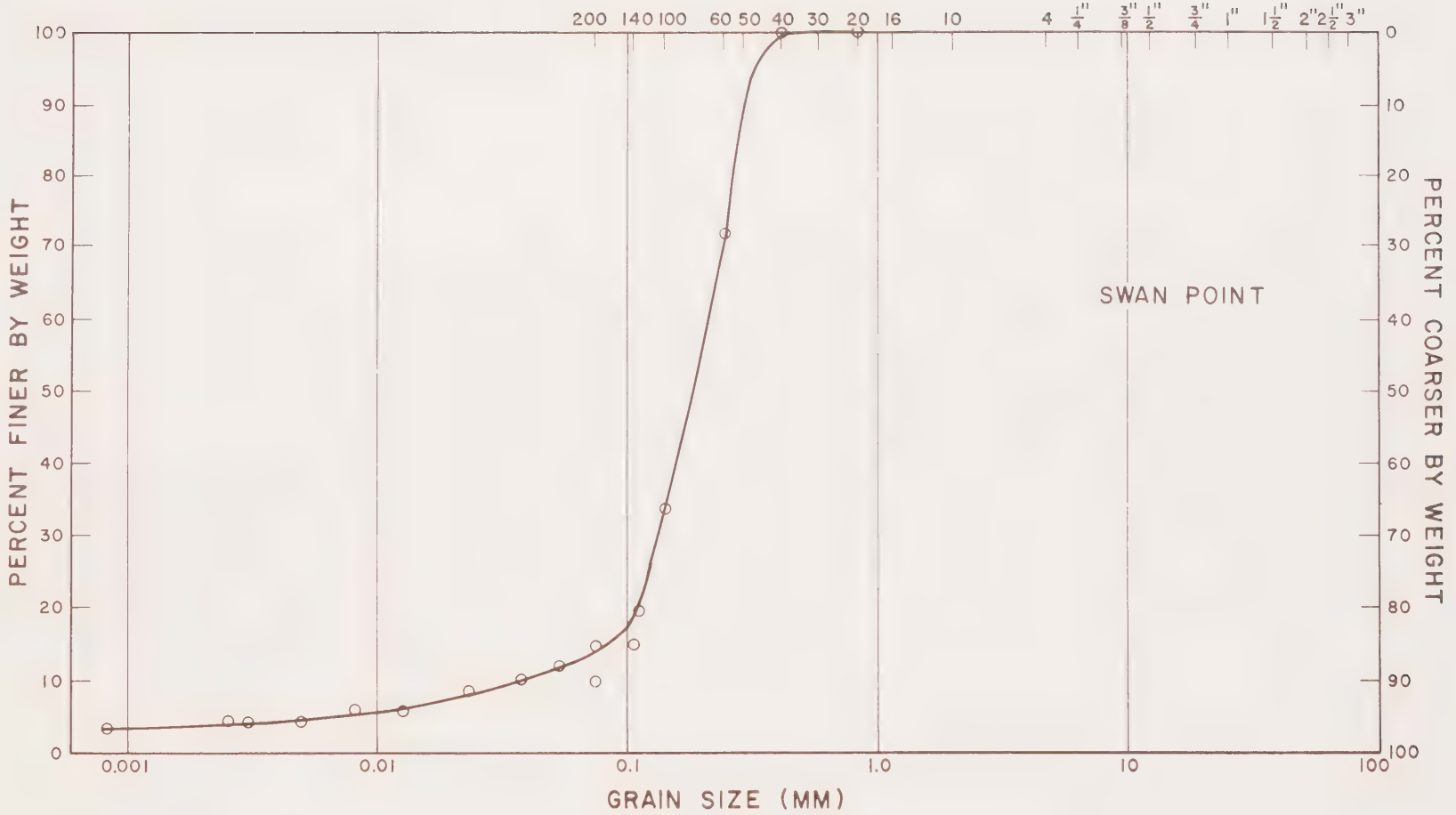


Figure 23. Grain size distribution of soil sample from 1.2 m depth, Swan Point, north bank of Liard River, Site 4.

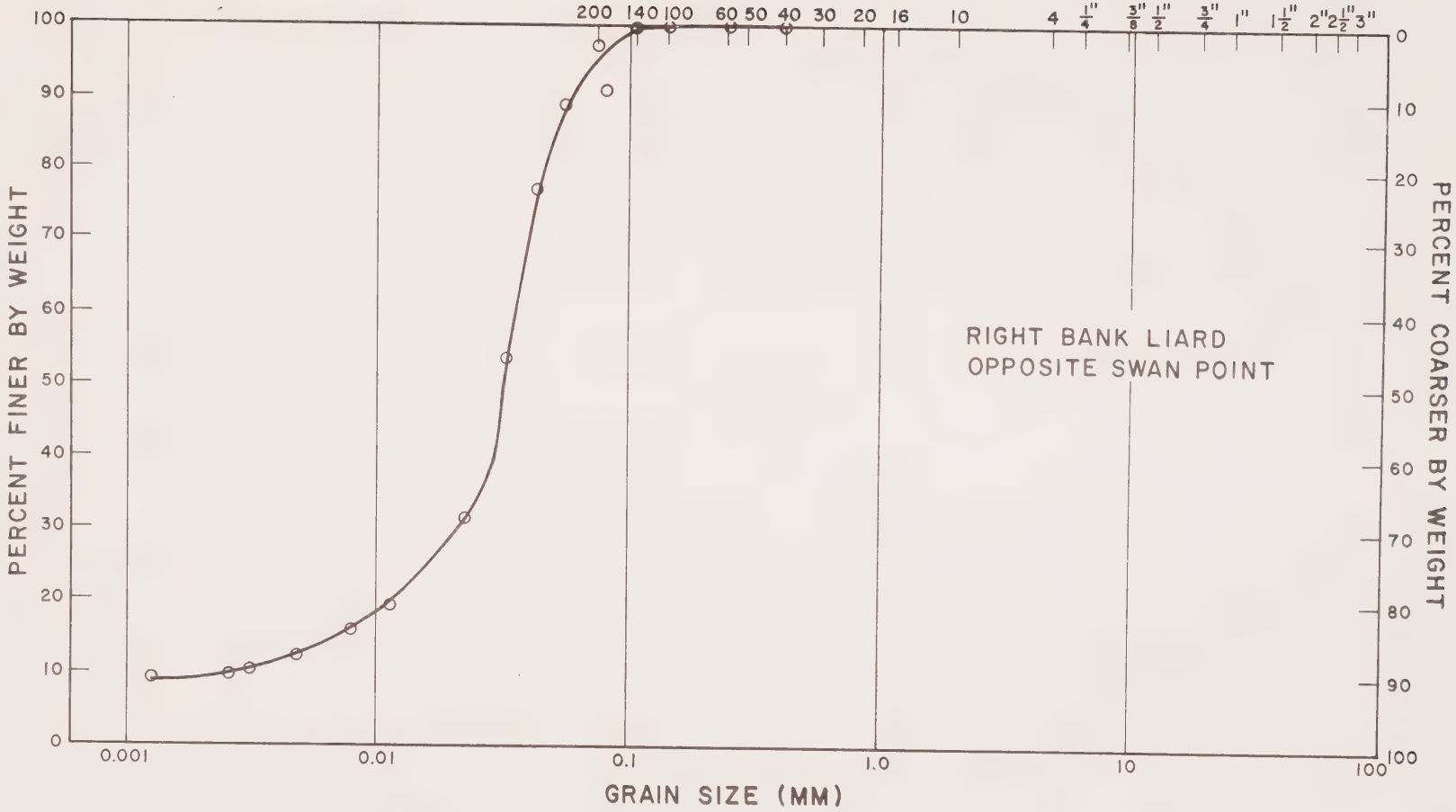


Figure 24. Grain size distribution of soil sample from 1.2 m depth, south bank of Liard River opposite Swan Point, Site 4.

HYDROLOGIC PROCESSES IN A SUB-ARCTIC UPLAND WATERSHED

by

C. D. Sellars

Technical Report 12 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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ABSTRACT

This report presents the results of the observations made on a small watershed in the foothills of the Mackenzie Mountains during the summer of 1972. The project is a fundamental study of the hydrologic processes in this region with emphasis on the time distribution of runoff quantities. The instruments used for data collection included six recording rain gauges and two water-level recorders. Storm excess waters were found to run off very quickly producing high flood peaks, and a large proportion of the rainfall appeared as runoff.

HYDROLOGIC PROCESSES IN A SUB-ARCTIC UPLAND WATERSHED

by

C.D. Sellars

Introduction

Throughout the proposed pipeline route along the Mackenzie Valley there are few quantitative hydrologic data. Discharges in the Mackenzie River and some of its major tributaries have been measured over a number of years but little is known about the magnitude of flows in the smaller tributaries. Furthermore, there are few climatic stations in the area and all of these are located at low elevations in the river valleys.

Providing adequate drainage for surface water is one of the more important aspects of pipeline construction particularly in the permafrost zone. Throughout the construction phase, decisions concerning various aspects of surface water drainage will have to be made constantly. Lack of hydrologic data may cause sections of a pipeline or road to be either under- or over-designed. Under-design of drainage facilities, even for very small streams, would lead to backing-up of water during high flow stages and consequent serious modification of the permafrost regime immediately adjacent to the pipeline.

Except for major rivers, only limited hydrologic data are available for analysis prior to the construction phase of a pipeline and it will be necessary to employ indirect determinations of runoff. Normally, indirect determination of extreme flows in areas almost totally deficient of hydrologic data is carried out by the use of empirical formulae or other rule of thumb techniques. However, these methods imply some basic knowledge about the hydrologic processes in the area. To acquire basic knowledge of these processes, particularly the relationship between rainfall and runoff, a small watershed study was undertaken in the foothills of the Mackenzie Mountains.

The watershed selected is situated in the headwaters of the Arctic Red River, on the edge of the Mackenzie Mountains. These mountains are the source area for major floods in Mackenzie River tributaries located on the west side of the Mackenzie Valley. The project undertaken is a fundamental study to gain a better understanding of the natural hydrologic processes in this region, with emphasis on the time distribution of runoff quantities. The specific objectives of this study are to collect meteorologic and hydrologic data on the selected watershed and to evaluate the relationship between rainfall and runoff. This will be done first by unit hydrograph techniques and, subsequently, by the development of a mathematical model which will integrate the effects of the various interrelating hydrologic phenomena and simulate runoff. This report presents the results of the first summer's observations.

Study Area

The criteria used for the selection of the watershed were: (a) the climatic data collected should fill a gap in the present widely-dispersed meteorological station network; (b) the basin should be typical of the region; (c) it should be small enough for precipitation input to the basin to be measured with reasonable accuracy; and (d) the basin should be reasonably easy of access.

The selected watershed is located at longitude 131° 16' West and latitude 65° 13' North, five km west of the Arctic Red River. Figure 1 shows the position of the watershed in the Mackenzie Valley Region and the location of climatic stations in the area. The nearest station is at Fort Good Hope, a distance of about 200 km.

No drainage basin can be truly representative of a region, but the watershed selected is typical of small basins in the Mackenzie Mountain foothills. The stream is known as "Twisty Creek" and drains an area of 6.55 km^2 measured at the main stream-gauging site. The elevation of the basin at this point is 674 m above mean sea level and the highest point in the catchment has an elevation of 1332 m measured with an aneroid barometer.

Characteristic features of the watershed are steep-sided valleys in the upper regions of the basin and a narrow gorge eroded into the limestone where the stream emerges from the mountains. The surficial geology consists of folded carboniferous rocks of the Devonian era, principally limestone and dolomite. Slopes in the upper part of the catchment consist of rock outcrops and talus with a complete absence of vegetation. Lower down in the basin, adjacent to the main stream, are glacial moraine slopes with thin coverings of grass in temporarily stabilized areas. On gentler slopes in the lower part of the basin are grasses and moss underlain by permafrost. Figure 2 is a photograph of the catchment taken from the highest point.

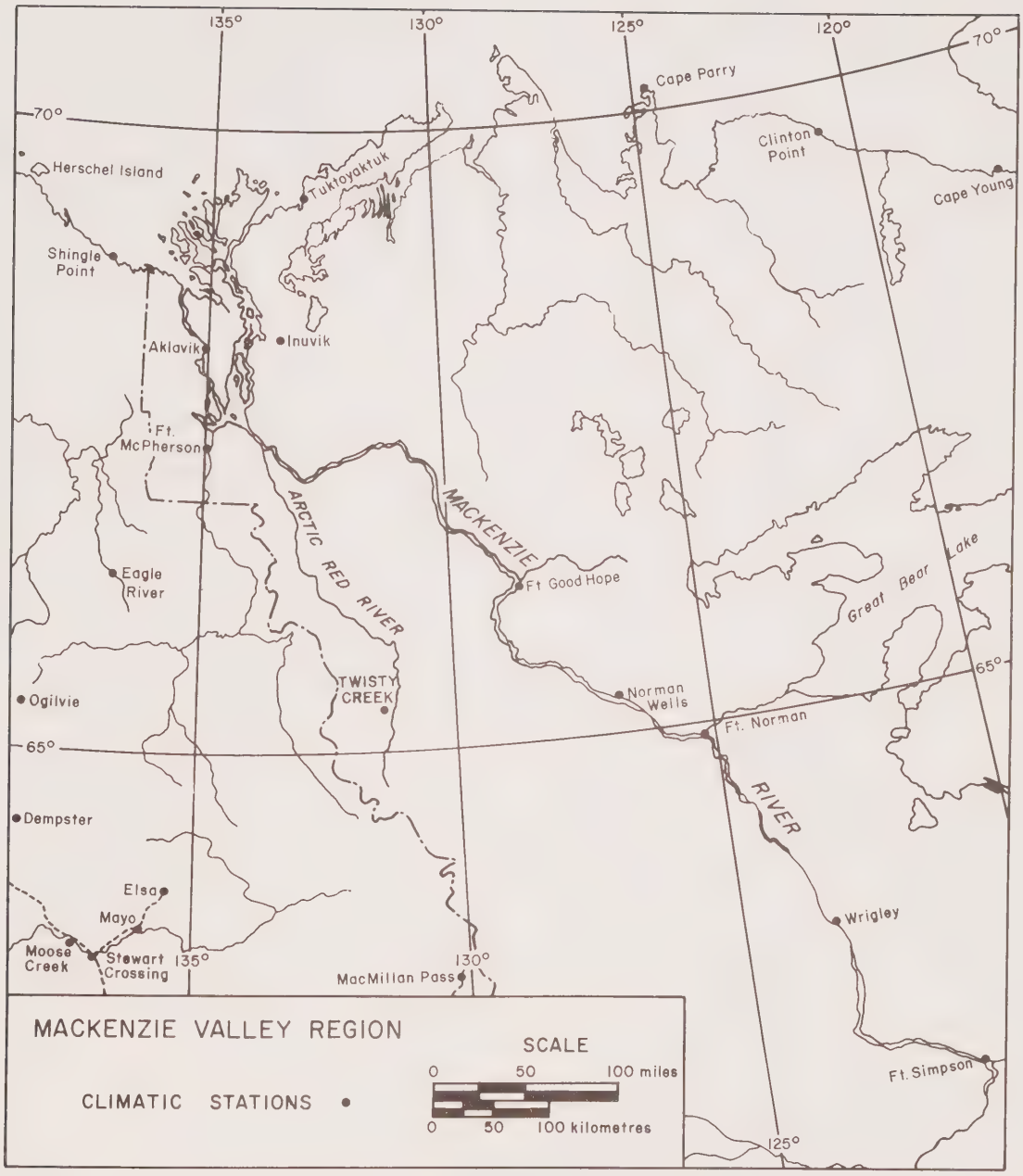


Figure 1. Mackenzie Valley region showing the location of the research watershed and climatic stations.



Figure 2. Photograph of the research basin taken from the highest point in the catchment. On the ridge in the foreground are the rain gauge, R5 and the Stevenson Screen, S3. In the distance, the Arctic Red River can be seen, flowing from right to left.

Methods of Data Collection

Climatic data. In the summer of 1971, an automatic weather station was installed adjacent to a lake suitable for landing aircraft at a distance of 5 km from the research watershed. This station provided information at three-hourly intervals on air temperature, ground temperature, wind speed, wind direction, solar radiation, barometric pressure and relative humidity. In addition, throughout the winter of 1971-72, a local trapper took meteorological observations and made routine checks on the weather station.

On "Twisty Creek" catchment, three Stevenson screens containing temperature and humidity measuring instruments were installed in June 1972, each at a different elevation. The elevations of the screens were 683 m, 841 m, and 1244 m above mean sea level and their positions in the catchment are shown in Figure 3. Each Stevenson screen contained one Lambrecht thermohygrograph model 252 C and maximum and minimum thermometers.

Precipitation data. In an area of considerable topographic relief such as "Twisty Creek", it was suspected that the spatial distribution of rainfall would be highly variable. Accordingly, a rain-gauge network density of one gauge per square kilometer was decided upon. This is, however, only the minimum recommended density by Holtan et al., (1962) for agricultural watersheds. In the case of "Twisty Creek", it was decided to distribute the rain gauges so that not only would they cover the total area uniformly but also that they would represent the total range of relief in the basin. However, in this area of rugged terrain it proved extremely difficult to find suitable rain gauge locations.

Six recording rain gauges were distributed over the watershed in June, 1972. All the gauges used were M.S.C. pattern tipping bucket rain gauges designed to react to units of 1/100 of an inch of rainfall. The location of each of the gauges is shown on Figure 3 and the elevation of the gauges above mean sea level is shown in Table 1.

Runoff data. Two Stevens Type F water-level recorders were installed in June 1972 on "Twisty Creek" at the locations shown on Figure 3. The principal site is located where the stream emerges from a steep-sided valley onto the sloping plateau at the base of the mountains. The second water-level recording site is located at the outlet of a gorge about one mile downstream from the main site.

One of the problems of installing water-level recorders in mountain streams is the location of the stilling well and the intake pipe. In a flashy stream, it is difficult to place the stilling well and intake pipe where water levels occurring during peak flows can be recorded without endangering the safety of the installation. Excavation of a stilling well site outside the main stream channel was not feasible. The problem was overcome by the use of a siphon intake to the stilling well as suggested by Church and Kellerhalls (1970). Use of this method allowed the stilling well to be located downstream from the water-level recording site and in a position of safety with regard to flood flows.

At the highest point of the siphon, a reservoir was connected to the system to collect air bubbles. A plastic bottle was used for this reservoir

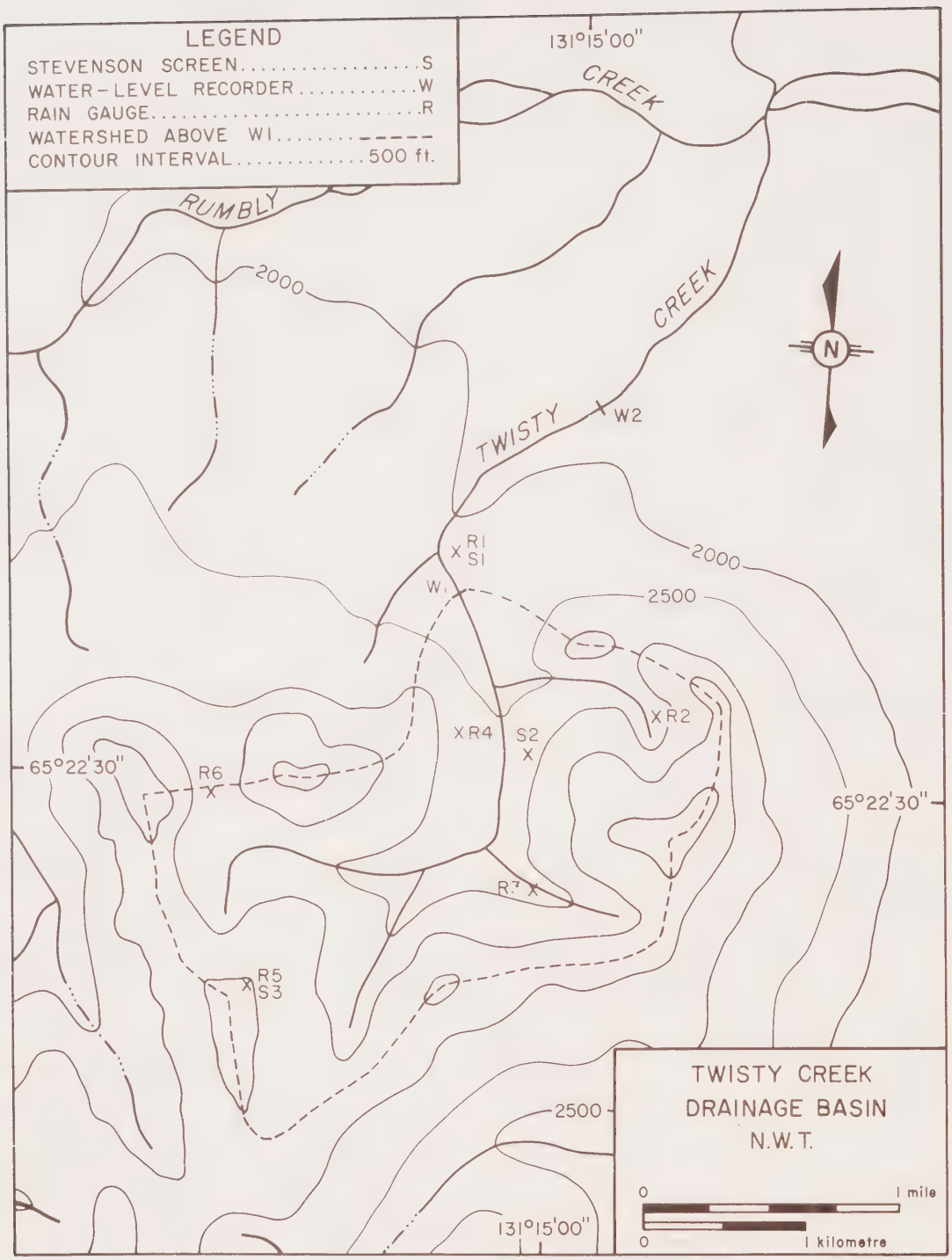


Figure 3. Location of instruments on "Twisty Creek" drainage basin.

and some difficulty was experienced with the operation of the system as the bottle tended to collapse under adverse pressure conditions. This problem was overcome by insertion of reinforcing inside the bottle. At both water-level recording installations the existence of natural controls obviated the need for weir construction.

A semipermanent stream gauging site was set up near the principal water-level recorder. A bridge was constructed over the stream and a metal graduated tape fastened to it to facilitate measurements. Discharges were computed by integration of discrete velocity measurements over the cross-section. Velocity was measured by an Ott propeller meter (Fig. 4).

Data analysis. A stage-discharge relationship was developed for the principal water-level recorder site based on twelve discharge measurements made at the bridge. For the lower site a tentative stage-discharge relationship was developed for low flows based on three measurements. The record from the lower water-level recorder was discontinuous due to difficulties with the siphon intake system. Water-levels and associated times of occurrence were extracted from the recorder charts and punched on computer cards to facilitate the conversion from stage to discharge.

A simple, efficient system was devised for the conversion of the rain-gauge charts to digital data. For each gauge the time of occurrence of each 0.01 inch of rain was punched on computer cards. From this data, rainfall totals for any time interval could be computed. Specific rainfall events were totalled and the average rainfall over the catchment computed by the Thiessen method. Table 1 shows the area of the Thiessen polygon and the weighting factor for each rain gauge.

Individual hydrographs were plotted and the base flow subtracted for each storm. Runoff totals were computed by integration of the storm hydrograph. The total effective rainfall was thus calculated for each storm and the duration obtained from the rainfall hyetograph. The unit hydrograph was obtained by dividing the ordinates of the storm hydrograph by the total effective rainfall.

Results

Climate. Climatically the area is characterized by long winters and a short summer lasting three months from June to August. Meteorological observations were made during the winter from November 28, 1971 to March 19, 1972. During this period the maximum temperature recorded was -4°C in January and the minimum temperature -47°C. The total snowfall over this period was 543 mm and the average water equivalent in the snowpack on March 19, 1972 was 76 mm. These measurements were made 5 km from "Twisty Creek" and undoubtedly snowfall in the mountains was considerably higher. Due to difficulties with the operation of the automatic weather station, no data are available over this period from the station.

During the summer months the maximum temperature recorded on "Twisty Creek" catchment was 27°C at the Stevenson screen (S1), and the minimum recorded temperature at this site was 0°C. Temperatures measured at the S3 site at an elevation at 1244 m varied from -4°C to +18°C. The



Figure 4. Photograph of the method of measuring stream velocity. The bridge was constructed over a rectangular section, 10 ft wide and 6 ft deep.

average temperatures for the sites S1, S2 and S3 were 13°C, 12°C and 8°C respectively.

The total rainfall at each rain gauge over a 55-day period from July 2 to August 25, 1972 is shown in Table 1 and isohyets plotted from these values are shown in Figure 5. The average rainfall over the catchment during this period was computed as 232 mm.

Generally, rainfall increased with elevation; however, the gauge at the highest elevation (R5) did not record the highest total rainfall. Many of the rainfall events recorded in the summer of 1972 were orographic and convectional in nature with rain clouds approaching the basin from the low-lying areas to the north. In these cases, gauge R5 was in the rain shadow caused by peaks immediately to the north where the highest total rainfall was recorded (gauge 6). As McKay (1964) pointed out, although precipitation on the average increases with height, the highest short-duration rates may be found at lower elevations because of the relative availability of precipitation moisture. In the long run, however, very high elevations receive more precipitation because of a greater frequency of occurrence. Records from a 55-day period are not long enough to verify or negate this statement, but the highest short-duration rates were measured at a relatively low altitude (gauge R3). In a 30-minute period on August 8, a total rainfall of 11.4 mm was measured at this gauge.

Table 2 is a summary of the rainfall and runoff records presented on a daily basis collected over a 41-day period. The storm on August 8 produced a peak flow which was 36 times greater than the mean discharge. This flood deposited approximately 70 tons of gravel and boulders on the water-level control section (which had previously consisted of bedrock for a period of at least a year). This changed the stage-discharge relationship and although water levels were recorded until the end of August, little confidence could be placed in the accuracy of the computed discharges. The recession curve of the August 8 storm hydrograph was interpolated from discharge measurements made at the bridge. The peak flow was also measured at the bridge.

All the rain gauges were operating correctly by July 2 and the period of complete, accurate records lasted from that date until August 11. During this 41-day period the total runoff was 73% of the total rainfall. This figure is extremely high and indicates small evaporation losses on the watershed. The period from July 12 to 17 was relatively dry and isolated storms had little effect on the streamflow. Groundwater replenishment and evaporation took account of the losses and the discharge never rose above 0.1 m^3/s except on July 2 when the stream was still in recession from a previous storm. The period from July 18 to August 11 was a relatively wet period and runoff totalled 74% of the rainfall. The discharge in "Twisty Creek" at the beginning of this period was 0.05 m^3/s and at the end of the period 0.10 m^3/s.

Groundwater. Although "Twisty Creek" is a flashy stream, hydrographs were observed to have extended recession curves; this indicates substantial groundwater flow in the basin. Over most of the basin, groundwater is stored in solution cracks in the carboniferous rocks. In dry periods, very little direct runoff would occur following a rainfall and most of the water appeared to enter groundwater storage. Figure 6 shows the hydrograph

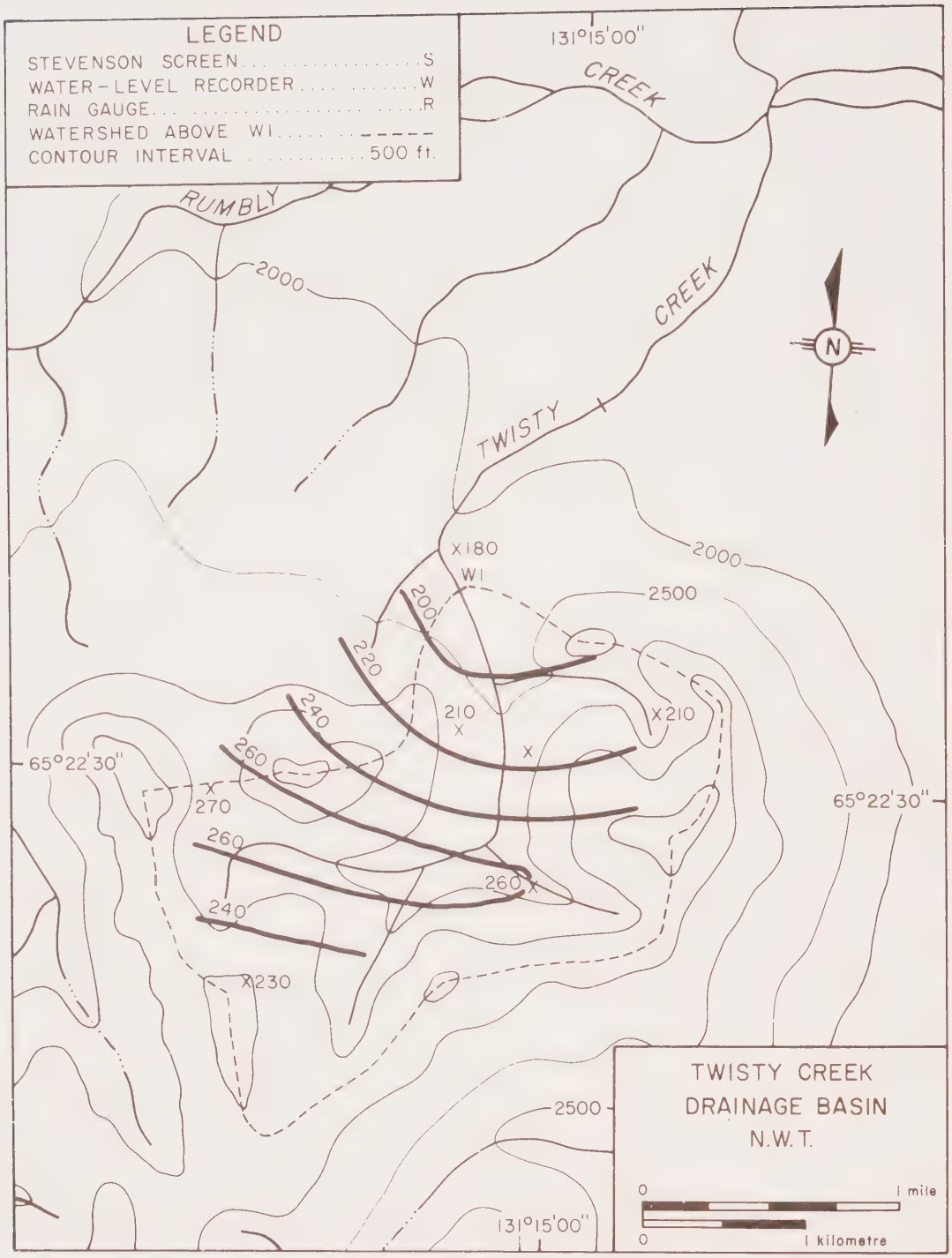


Figure 5. Isohyetal map of rainfall totals over a 55 day period. Rainfall totals in mm.

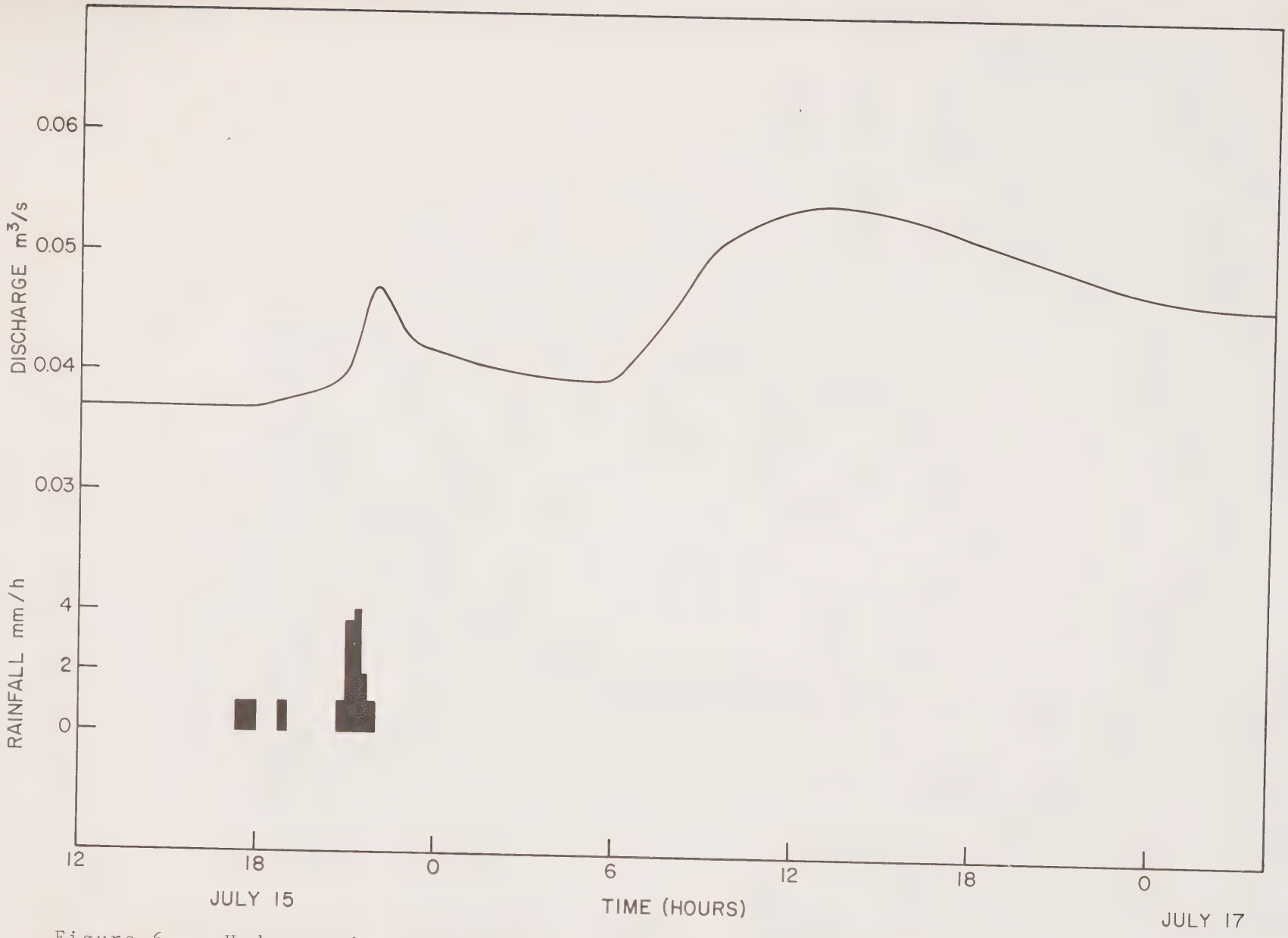


Figure 6. Hydrograph produced from total rainfall of 3.9 mm.

produced from a rainfall of 3.9 mm on July 15. The first peak in the hydrograph is the direct runoff which occurred very quickly after the rainfall, and reached a peak as the rainfall ceased. The second peak is the groundwater flow which did not start to increase until 8 h after the cessation of rainfall. The groundwater runoff peaked at a slightly higher level than the direct runoff some 15 h after the rainfall. This phenomenon which was repeated on July 17, proved invaluable in estimating the quantity of groundwater flow at any given time in the basin.

On July 12, water ceased to flow in "Twisty Creek" at a point 100 m upstream from the lower water-level recorder site. Pools in the creek bed drained quickly by seepage, indicating that the groundwater table in the immediate vicinity of the stream had fallen below the level of the stream bed. During this time, the discharge upstream was fairly constant at 0.04 m^3/s, which indicated that at least this quantity of streamflow was by-passing the lower water-level recording site by seepage through solution cracks in the limestone at any given time over the period of record.

Storm runoff. Seven rainfall events produced hydrographs suitable for analysis during the period of record. Six of the flood peaks were in the range 0.8 - 2.2 m^3/s, but the storm on August 8 was of a different order of magnitude and produced a peak flow of 9.15 m^3/s. The results obtained from the analysis of this storm are presented here in detail.

The antecedent conditions in the catchment were such that very little of the storm water went into storage. About 20 mm of rain fell on the catchment during the two days prior to the storm and at the onset of the storm the main stream was flowing at a rate of 0.54 m^3/s or approximately twice the mean flow.

The storm lasted about three hours and the total rainfall was 22 mm averaged over the catchment. The isohyets (Fig. 7) generally followed the contours of the basin. Figure 8 is a photograph taken just downstream from the upper water-level recorder at the peak of the flood. It illustrates the turbidity of the water due to the high sediment content. During the flood, creek banks in glacial clay sediments suffered substantial erosion. For comparison purposes, flow in "Twisty Creek" under normal conditions is shown in Figure 9 when the stream was discharging at 0.3 m^3/s.

A unit hydrograph calculated from this flood is shown in Figure 10. The duration of excess rainfall was 2.25 h, the unit hydrograph peak 0.3 mm/h, and the lag time computed as 2.5 h. The definition of lag time was taken as the time elapsed between the centroid of the mass of effective rainfall and the centre of area of the unit hydrograph.

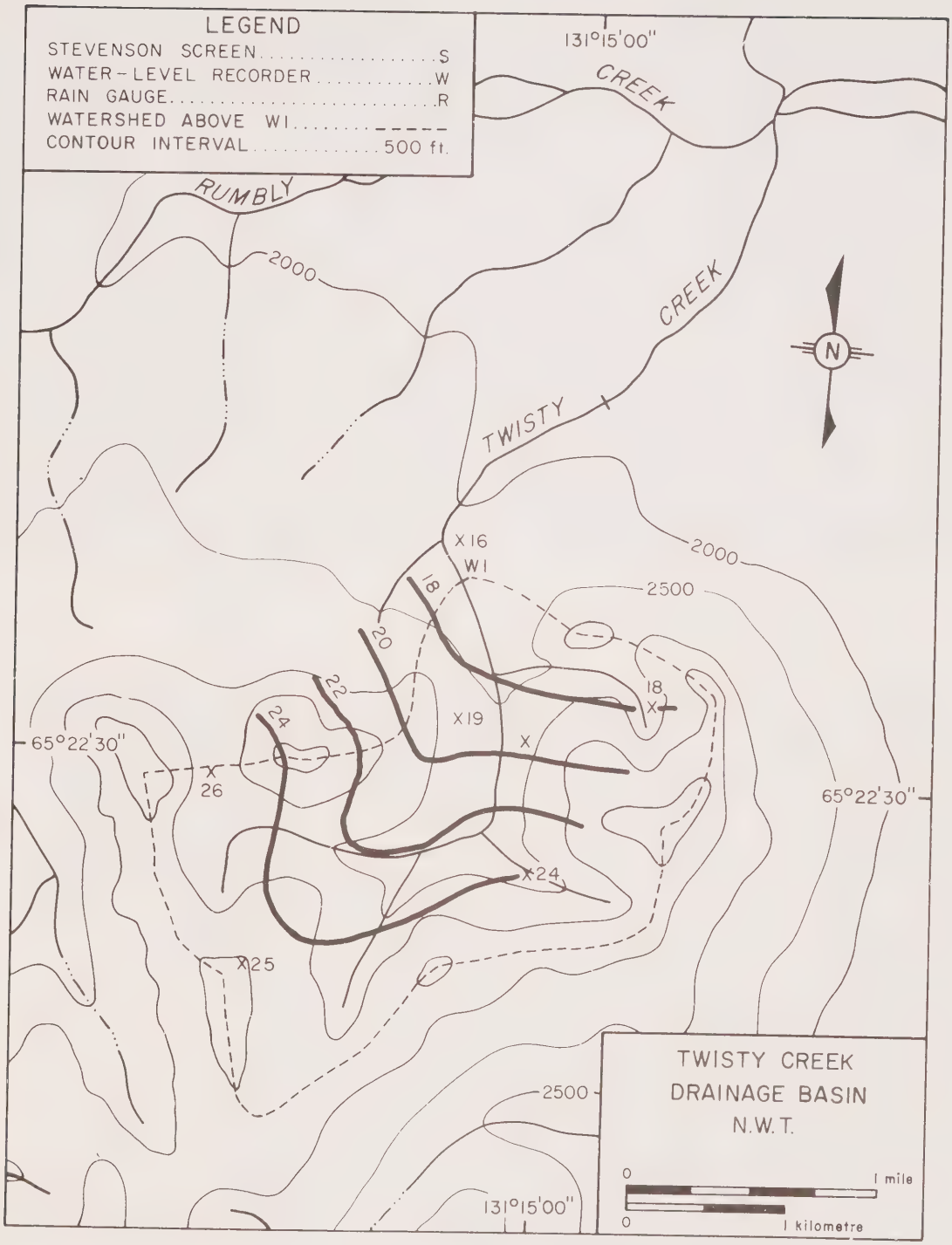


Figure 7. Isohyetal map of storm on August 8, 1972. Rainfall totals in mm.



Figure 8. Photograph of "Twisty Creek" at flood stage. The water-level recorder can be seen in the background.



Figure 9. Photograph of "Twisty Creek" during normal flow conditions.

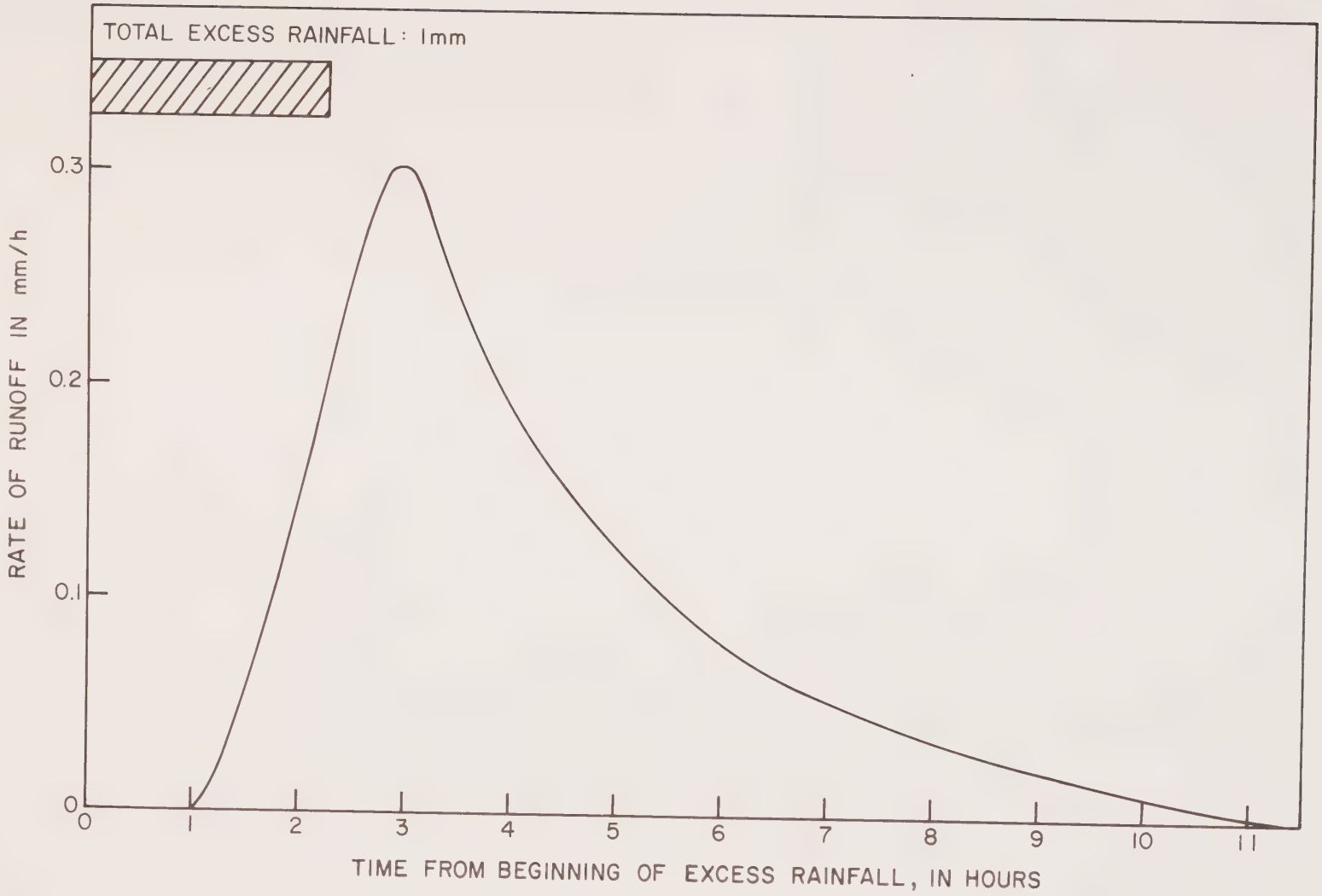


Figure 10. Unit hydrograph computed from storm on August 8, 1972.

Conclusions

The collection of hydrologic data for "Twisty Creek" was made during a single summer, which is too short a period in which to make definite conclusions. However, several hydrologic characteristics were observed which are relevant to the region as a whole.

The tentative conclusions are as follows:

1. The mean rainfall was 4 mm/day over a period of 55 days.

2. The mean runoff was 3 mm/day over a period of 41 days.

3. Heavy rain storms were produced orographically by systems approaching from the NW, N and NE.

4. Storm excess waters appeared as runoff extremely quickly in this upland catchment. However, the rate may have been slowed by extensive talus and interflow through solution cracks in the carboniferous rocks. The lag time for the catchment was computed as 2.5 h.

5. Groundwater flow is substantial; in areas away from the steep mountains the groundwater table in the vicinity of the stream may fall below the stream bed during dry periods.

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Holtan, H.N., N.E. Minshall, and L.L. Harrold, 1962. Field Manual for Research in Agricultural Hydrology. Soil and Water Conservation Division, Agricultural Research Service, Washington, D.C.

McKay, G.A., 1964. Meteorological Measurements for Watershed Research. Proceedings of Hydrology Symposium No. 4, National Research Council Sub-committee on Hydrology, Ottawa, Ontario.

Table 1. Rain-gauge data from "Twisty Creek" Basin, N.W.T.

Gauge	Type	Elevation m	Area km^2	Weight %	Total Rainfall mm
1	Daily	683	0.12	1.8	182.87
2	Daily	856	1.03	15.8	209.55
3	Daily	823	1.27	19.3	261.62
4	Daily	841	1.58	24.1	209.30
5	Weekly	1244	1.68	25.7	230.63
6	Weekly	1042	0.87	13.3	268.22

Table 2. Daily rainfall and runoff records over a 41-day period

"Twisty Creek" Basin, N.W.T.

Date 1972		Rainfall mm 1	2	3	4	5	6	Runoff mm	Mean disch. m^3/s	Peak disch. m^3/s
July	2	0	0.25	3.05	1.52	2.29	0.25	1.26	0.10	0.13
	3	0	0	0	0	0	0	1.18	0.09	
	4	0	0	0	0	0	0	0.82	0.06	
	5	0	0	0	0	0	0	0.65	0.05	
	6	0.25	0.51	1.52	0.51	0.76	1.78	0.62	0.05	
	7	2.79	2.79	3.05	2.54	1.27	3.81	0.73	0.06	0.06
	8	0	0	0	0	0	0	0.69	0.05	
	9	0	0	0	0	0	0	0.55	0.04	
	10	0	0	0	0	0	0	0.51	0.04	
	11	0	0	0	0	0	0	0.51	0.04	
	12	0	0	0	0	0	0	0.50	0.04	
	13	0	0	0	0	0	0	0.50	0.04	
	14	2.03	1.27	0.51	2.54	0.51	0.25	0.49	0.04	0.04
	15	3.56	4.06	4.83	4.06	3.30	6.35	0.48	0.04	0.05
	16	0	0	0	0	0	0	0.66	0.05	0.05
	17	2.54	2.29	5.08	5.08	3.81	17.02	0.65	0.05	0.05
	18	4.83	7.87	11.68	7.37	10.16	8.64	1.51	0.12	0.81
	19	0	0.51	0.51	0.25	0	0.51	1.63	0.12	
	20	14.99	17.27	19.81	16.00	18.54	16.26	8.08	0.61	2.23
	21	8.38	10.16	15.75	6.35	10.41	11.94	6.81	0.52	1.04
	22	7.11	8.89	18.80	13.21	25.15	16.00	14.83	1.12	2.23
	23	3.81	4.57	7.37	5.33	5.84	9.91	7.30	0.55	0.60
	24	0.25	0.25	0.76	0.25	0.51	1.02	5.08	0.39	
	25	0	0	1.02	0.51	0.51	0.51	2.44	0.19	
	26	0	0	0	0.51	0.25	0.76	1.55	0.12	
	27	0	1.02	1.02	0	0.25	1.02	1.16	0.89	
	28	12.45	12.70	12.70	12.19	10.67	12.19	1.51	0.12	0.39
	29	0.25	0	0.76	0.51	2.03	1.02	3.13	0.24	
	20	0	0	0	0	0	0	1.60	0.12	
	31	1.52	1.02	0.51	1.02	0.51	3.30	1.21	0.09	
Aug.	1	13.97	16.26	22.61	14.73	13.46	21.84	3.46	0.26	
	2	5.84	7.62	12.95	8.13	8.64	10.92	9.72	0.74	1.70
	3	0	0.25	0	0	0.51	1.02	6.18	0.47	
	4	0	0	0	0	0	0	2.57	0.20	
	5	0	0	0	0	0	0	1.61	0.12	
	6	12.95	15.24	14.99	14.99	14.73	13.72	1.30	0.10	
	7	2.29	9.91	14.73	5.84	12.45	8.38	5.14	0.39	0.88
	8	23.11	23.62	33.78	24.64	32.00	32.77	15.70	1.19	9.15
	9	1.27	2.03	2.29	1.78	1.27	1.78	17.41	1.32	
	10	0	0	0	0	0	0	3.21	0.24	
	11	0	0	0	0	0	0	1.82	0.14	
Totals		124.20	150.37	210.06	149.86	179.83	205.23	136.74	0.25	

Average rainfall over catchment: 186.18 mm in a 41-day period.

PRECIPITATION FREQUENCIES AND INTENSITIES ALONG PROPOSED PIPELINE ROUTES IN THE MACKENZIE VALLEY, N.W.T.

by

K. Swami

Technical Report 13 To
Glaciology Division
Water Resources Branch
Department of the Environment

Under The

Environmental-Social Program
Northern Pipelines

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ABSTRACT

An analysis of precipitation intensities and frequencies along the Mackenzie Valley suggests that there are slight regional variations of precipitation within the Mackenzie Valley area. Relatively low frequencies of extreme events were observed during the summer months, while even fewer occurrences were recorded during the winter. In general, the precipitation is relatively light in the northern part of the region as compared with other stations located further south along the valley. Analysis of daily temperatures indicates that, except in summer, a marked cyclical pattern is apparent. In winter the temperatures oscillate below the freezing point, but in spring and summer the temperature regime produces alternating periods of freeze and thaw.

Precipitation Frequencies and Intensities along the Proposed Pipeline Route in the Mackenzie Valley Region

K. Swami

INTRODUCTION

The winter atmospheric circulation in the Mackenzie Valley region is largely dominated by the presence of high pressure systems and low atmospheric humidity. In summer, however, with an increase in the occurrence of low pressure systems and higher atmospheric humidity, precipitation increases markedly.

A review of existing literature on the Canadian Arctic's regional climatology indicates that a synoptic approach has generally been followed. Moreover, the time scale of such analyses has, in most cases, been in terms of monthly or annual totals and little attention seems to have been given to day-to-day conditions.

The purpose of the present report, therefore, is to consider relevant meteorological elements from the viewpoint of their day-to-day occurrence. Particular attention will, moreover, be paid to the frequency and intensity of precipitation occurrences which may influence the hydrological balance and the surface runoff along proposed pipeline routes.

The stations at which statistical climatological data were obtained are shown on Figure 1. Mackenzie Valley stations fall into three groups representing the northern, central and southern regions respectively. The stations of the northern region are Nicholson Peninsula, Tuktoyaktuk, Inuvik, and Aklavik;Fort Good Hope, Norman Wells and Wrigley comprise the central region;Fort Simpson, Fort Providence, Hay River and Yellowknife are representative of the southern region.

Climatic observations for at least 10 years (1957-67) were obtained from the Data Acquisitions Section of the Atmospheric Environment Service. In some cases the records extend to 11 or 14 years, but in all cases at least 10 years of daily records were used. The data used in this study were taken from daily climatological observation 04 type cards. These cards give the summary for a climatological day. The elements reported are the maximum and minimum temperatures, 24-hourly amounts of rainfall, snowfall and total precipitation, 6-hourly precipitation totals, maximum and minimum relative humidity (where available), snow depth and occurrence of various phenomena such as thunderstorms, hail etc. (Thomas, 1972).

CLASSIFICATION OF PRECIPITATION

For purposes of analysis, the daily precipitation totals have been divided into classes representing different amounts as follows:

Class 1 — no precipitation

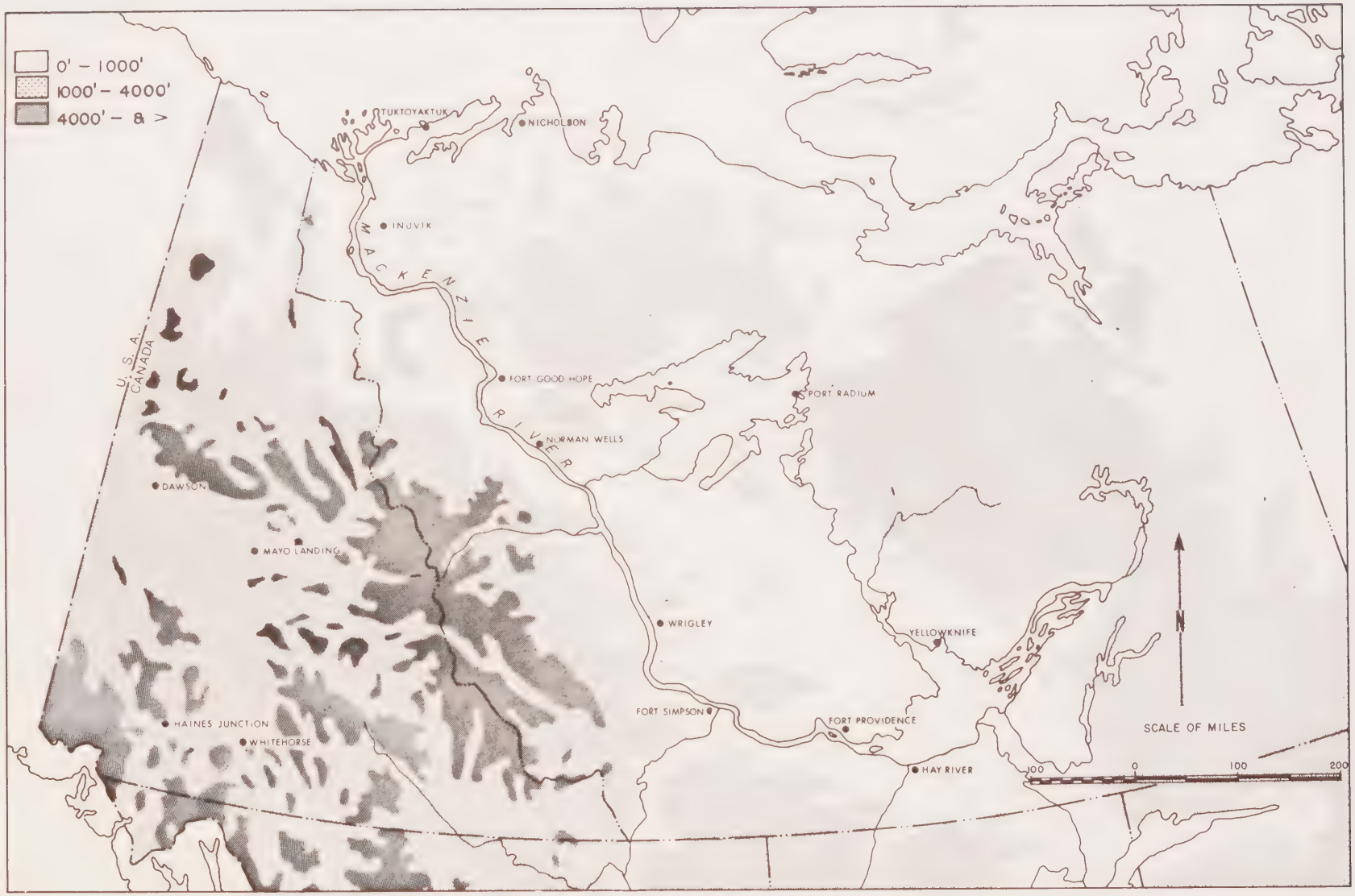


Figure 1. Location of principal first order and climatological stations in the Yukon and Northwest Territories.

Class 2	0 - 5 mm
Class 3	6 - 10 mm
Class 4	11 - 15 mm
Class 5	greater than 15 mm

In this classification a trace of precipitation has been listed in Class 1 (no precipitation).

The classes were chosen as being characteristic of the general range of frequently-occurring precipitation amounts. The use of smaller intervals, although it would have provided more detail, would not have altered the essential conclusions. To fit the classification, snowfall was converted into equivalent inches of precipitation, using the standard AES conversion scale of 10" of snow equal to 1" of water (254.00 mm of snow equal to 25.40 mm of water).

RESULTS OF PRECIPITATION CLASSIFICATION

The distribution of precipitation over the year by classes is indicated on Figure 2. The diagram shows the actual number of occurrences in each class over the period of record. Each category is grouped according to the 12 months of the year. Thus Class 2 precipitation reveals the total frequency as it occurred over 10 January months, 10 February months, etc. over the test period.

It is apparent that Class 2 precipitation is frequent at all stations and is prevalent all year round. This seems to be the general pattern throughout the Mackenzie Valley as no clear cut differences can be observed from one region to another. However, it is noticeable that around the middle of the year (May-July) there is a decrease in the number of Class 2 cases, and at about the same time there is an increase of Class 3 precipitation. This observation does not signify a relative decline in precipitation as a whole, but indicates that precipitation is less frequent in this month. Class 4 does not manifest anything of special significance. The majority of Class 5 occurrences take place during the summer months. This predominance is particularly well defined in the northern and central Mackenzie regions. In the south, although Class 5 tends to a maximum in summer, the frequencies of days with precipitation in this class are on the whole greater and are spread over longer time periods than is the case further north.

The balance of the different groups of precipitation over time is indicated in Figure 3. The percentage frequencies have been calculated on a monthly basis over the test period (1957-67). Thus Figure 3 shows the percentage distribution of categories typcial for any given month of the year and illustrates the relative importance of the Class 3 group (6-10 mm) of precipitation.

Figures 2 and 3 show that Class 2 precipitation is the most frequently occurring class in all months of the year. The occurrence of precipitation in other classes is largely confined to summer months. Although relatively infrequent, however, the amount of precipitation associated with the latter

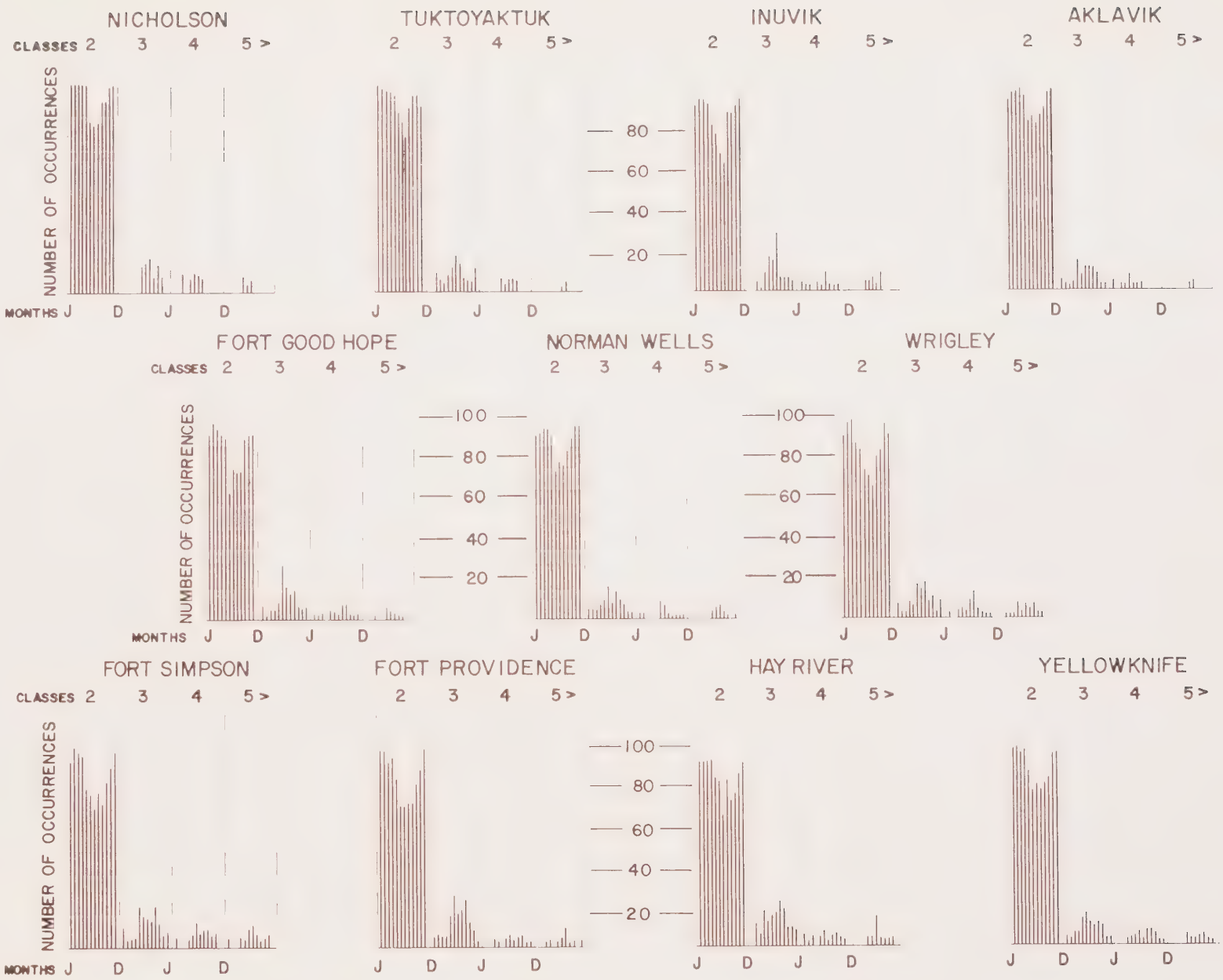


Figure 2. Frequency of precipitation occurrences in different classes by months (1957-67).

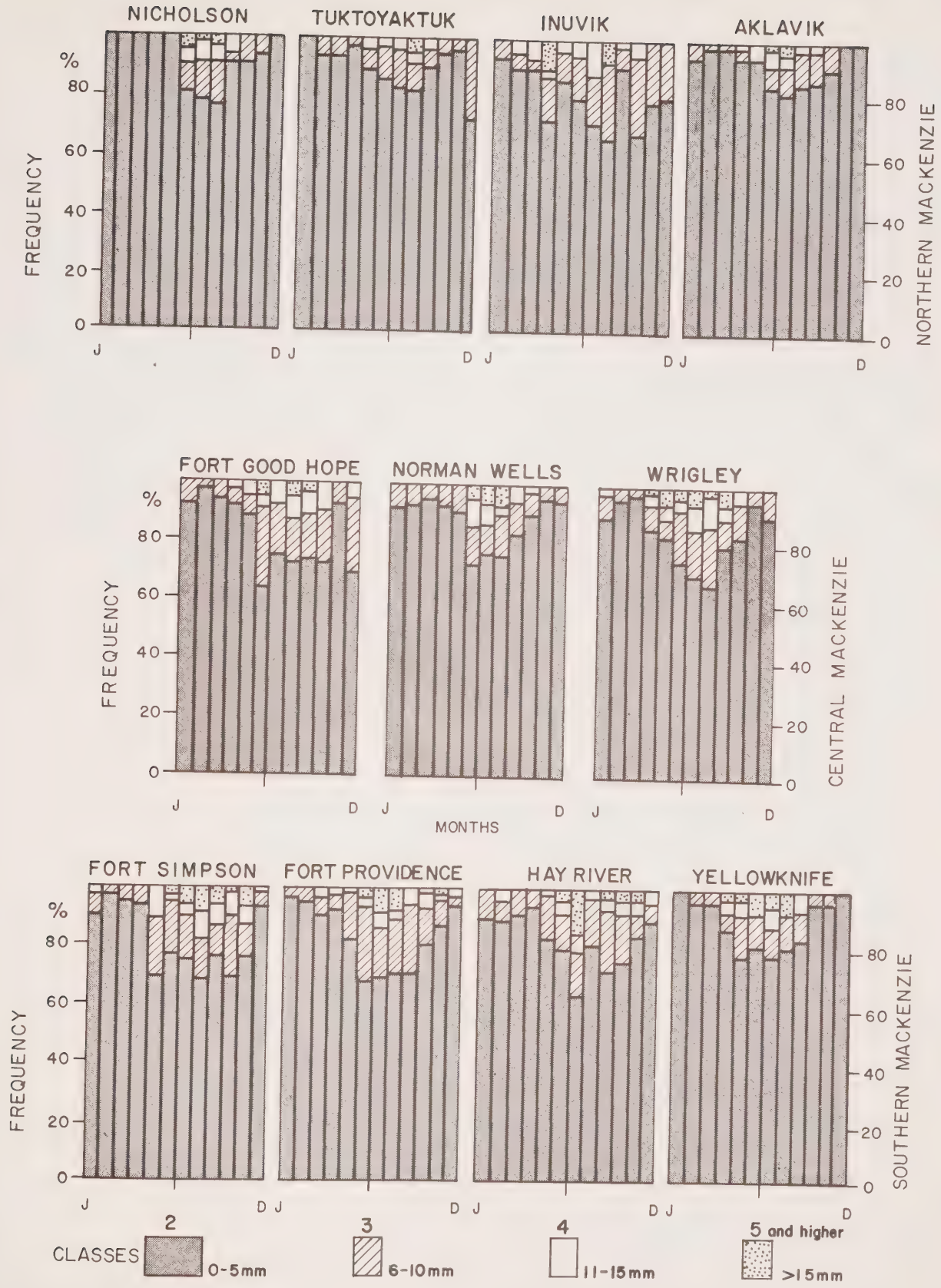


Figure 3. Percentage Frequency of Precipitation Occurrences in Different Classes.

classes is greater than that of Class 2 (see Table 1). Table 1 lists information on percentage frequency and total precipitation associated with each precipitation class at each of the stations analysed. It can be seen that Class 2 in summer months brings 30% or less of the total precipitation, whereas in winter this class is responsible for nearly all (80% or higher) of the precipitation which occurs. The higher rainfall classes, by contrast, are in summer the major contributors to total precipitation. It is noticeable that Classes 3 and 5 are the more important in this respect. Class 3 is responsible for some 30% or more of a station's summer precipitation and Class 5 for a similar percentage, despite the fact that the percentage frequency of occurrence of Class 3 is normally less than 30%, while Class 5 rarely exceeds 10% in frequency of occurrence.

VARIABILITY OF CONDITIONS

Much has been said so far about significant and meaningful amounts of precipitation along the Mackenzie Valley and their annual distribution. Another aspect of concern is the variability of precipitation and its deviation from the standard levels that are characteristic of each station. Variability is a potential climatic characteristic and is of special importance in hydrological studies.

To evaluate the degree of variability, an analysis of total annual precipitation was made to give a measure of the variations that are to be expected. A variability test commonly known as the Inter-sequential variability (ISV) was applied to the annual totals of each of the 10 or more years of record available for the investigations.

The ISV is determined by the quantity as well as the sequence of the series of numbers characterizing the variations of annual precipitation. The equation employed was (Conrad and Pollack, 1962):

$$ISV = \frac{\varepsilon/D/}{n-1}$$

where D = difference between two consecutive precipitation totals and
n = number of cases

The statistics which represent the ISV are used to calculate separately the average amount of increase or decrease of precipitation from year to year, and are valuable for any long-range forecasting of probable trends.

The results of the analysis for the Mackenzie region are shown in Table 2. There is relatively little deviation in the northern Mackenzie region, the greatest deviation being at Inuvik with a difference of 55 mm of precipitation. The central region has more internal variation than is the case in the northern region. Norman Wells, for example, has a fairly small variability (ISV = 58 mm), whereas the other two stations have a variability of ISV = 103 mm and 118 mm. In the southern region, the ISV values vary from 38 mm at Yellowknife to 117 mm at Fort Simpson. The stations at Yellowknife, Fort Providence and Hay River, which are of intermediate variability, lie some distance away from the pipeline routes as currently proposed by industry.

EXTREME EVENTS

In the present context an extreme precipitation event is defined as one in which more than 15 mm of precipitation (water equivalent) falls in a 24-hour period. The frequency of such falls can be seen from Table 1 as being normally less than 10% of the total occurrences in any month. They are most common in summer months (Fig. 4) but do not necessarily occur every year (Table 3). Although they do not occur frequently, their contribution to total precipitation can be high. This feature is illustrated in Figure 5 which compares the frequency of occurrence of falls of precipitation over 15 mm in 24 hours with the percentage of the total precipitation produced by such cases. The large amount of precipitation suggests that their significance for the local environment is much greater than their frequency of occurrence might indicate. In this connection it should be noted that sometimes these large amounts of precipitation are in the form of snow. Although this is rare, the different potential effect of snow and rain on pipeline development (snow accumulation on one hand and surface runoff from rain on the other) is recognized in the presentation of an analysis of extreme events as snow and rain in Table 4.

During the summer months, the Mackenzie region is affected by thunderstorms. Lightning associated with these storms is an important cause of forest fires in the region. An analysis of the frequency of high-rainfall occurrences in conjunction with these thunderstorms was made and it was found that the number of cases when a thunderstorm was accompanied by heavy precipitation was small. A summary of results is shown below:

Northern Mackenzie	17 thunderstorms over the period-- none with rainfall greater than 15 mm
Central Mackenzie	29 thunderstorms over the period-- 3 with rainfall greater than 15 mm
Southern Mackenzie	44 thunderstorms over the period-- 6 with rainfall greater than 15 mm

The fact that so few of these storms yield extreme rainfalls makes them an even greater threat with regard to forest fires.

DURATION OF PRECIPITATION

In an environmental sense, intensity of precipitation can be equally, if not more important than, the quantity of precipitation. Moreover, a large total in 24 hours does not necessarily imply a higher intensity than a smaller total in the same period. Therefore some consideration of the duration of precipitation within a given 24-hour period is necessary. For such an analysis, hourly totals or precipitation would be desirable. However, for this report the the 6-hourly total from the 04 type card was used.

A sample of days with precipitation exceeding 6 mm was made for three stations, one in each region. The results of the analysis are given in Table 5. It can be seen from Table 5, that within the 24-hour period there is a relatively short time of concentrated precipitation which contributes most of the total fall. While this pattern of short-lived precipitation can be expected of extreme events, even the smaller 24-hour totals over 6 mm appear to have periods of high intensity. For example, at Fort Simpson on July

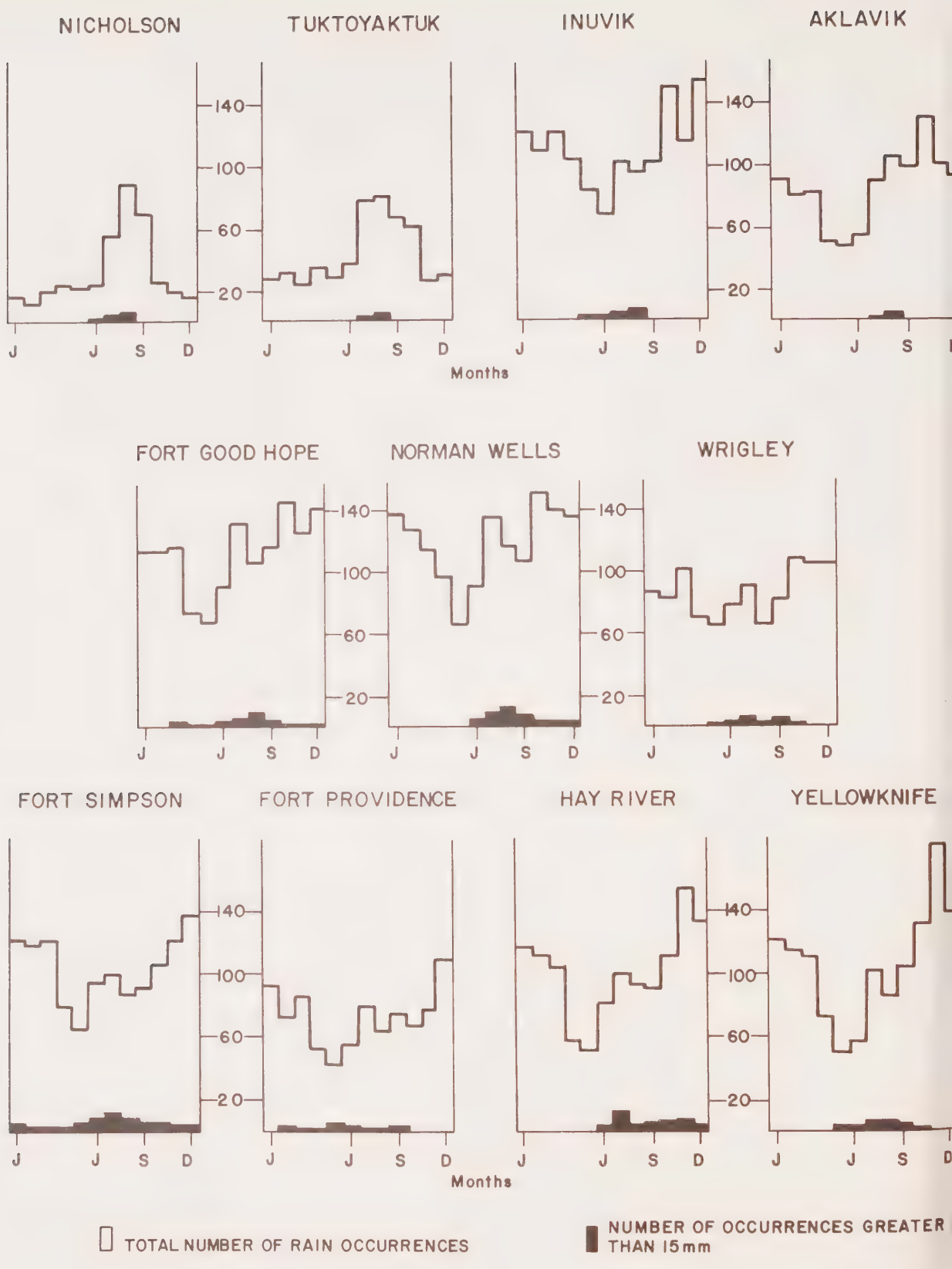


Figure 4. Monthly variation of precipitation occurrences (1957-67).

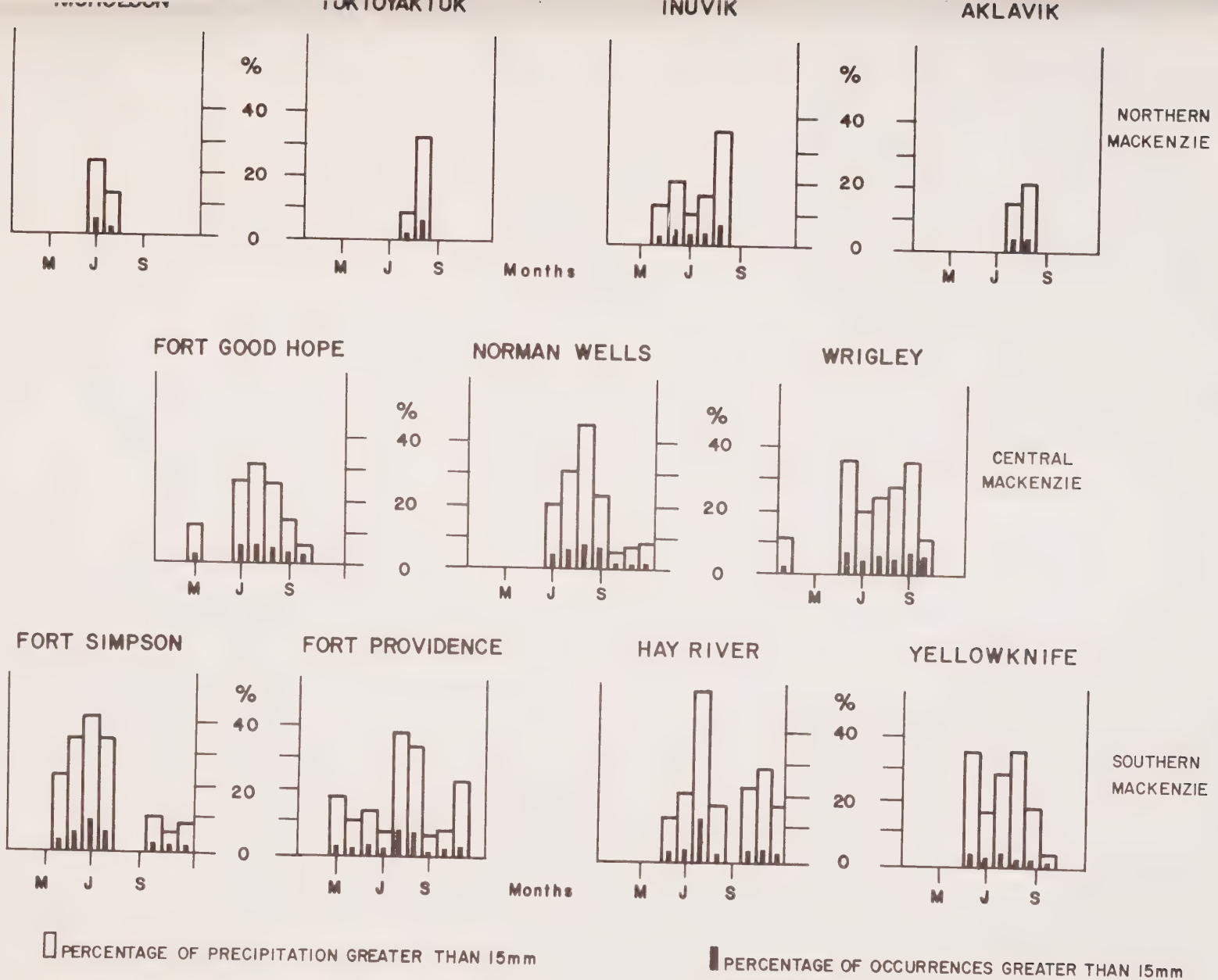


Figure 5. Analysis of precipitation greater than 15 mm per day (1957-67).

6, 1963 and at Inuvik on July 23, 1967, almost the entire precipitation recorded for those dates, 8 mm at each station, fell within a period of 6 hours. Details of duration and intensity of precipitation occurrences can be obtained only from recording charts. Such an analysis would greatly help in evaluating the effect of precipitation and its influence on the choice of a pipeline route.

TEMPERATURE ANALYSIS

As part of the investigation of climatic conditions, an analysis was made of mean daily temperatures (maximum and minimum) for stations along the Mackenzie Valley over the 10-year period. From this analysis, five-day moving averages were obtained. The resulting patterns revealed marked contrasts between summer and winter periods (Figs. 6, 6a and 6b).

During the winter months a wave-like pattern dominated the curve, suggesting cyclical movements of high and low temperatures. These tendencies were significant at all stations and were identified in the maximum and minimum temperature curves. It is of interest to note that when the air temperature rises above 0°C, the temperature fluctuations are much less pronounced, and at some stations cease to be present until the cold weather sets in again. It is noteworthy that the fluctuations are rhythmic, despite the relatively long period over which the moving averages were calculated. This suggests that a phenomenon occurs in the winter atmosphere which is repeated approximately at the same time each year.

With respect to the effect of these temperature fluctuations on the pipeline, it is interesting to note that the temperature surges which occur during winter tend to oscillate below freezing level. In summer by contrast the cyclical pattern disappears and temperatures are constantly above 0°C, with a relatively small diurnal temperature range. There is, however, a period in spring and another in autumn when regular fluctuations occur around the freezing point. Under such conditions regular freeze and thaw at ground level can be expected.

CONCLUSIONS

Based on the evidence from the climatic data, the following conclusions appear to be relevant to the pipeline route:

1. There tends to be more precipitation in the southern region of the Mackenzie than in the north, but there is little difference between the two regions in the seasonal pattern of precipitation through the year, or from one year to another.

2. Most of the data which were available for the present study are for stations on the east bank of the Mackenzie River. The precipitation analysis has accordingly been limited to stations located in the Mackenzie Valley. The results, therefore, may be considered as being representative of conditions in the valley only and should not be taken as being indicative of conditions further east or west of the valley itself.

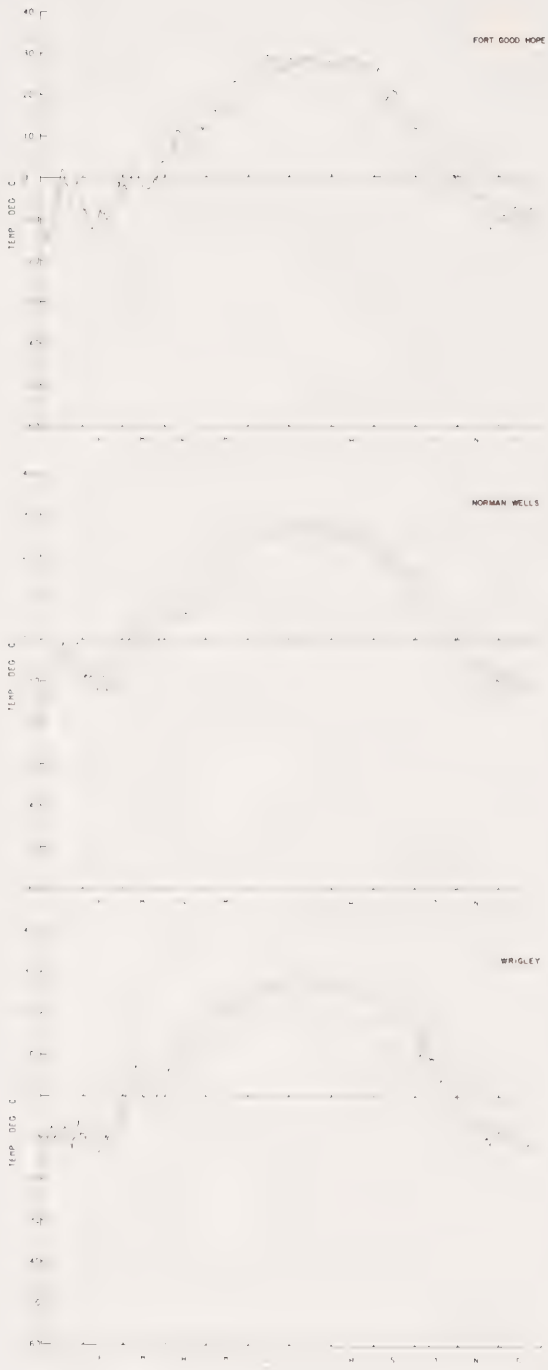




Figure 6.

Five day moving averages of maximum temperatures (1957-67).

Five day moving averages of minimum temperatures (1957-67).



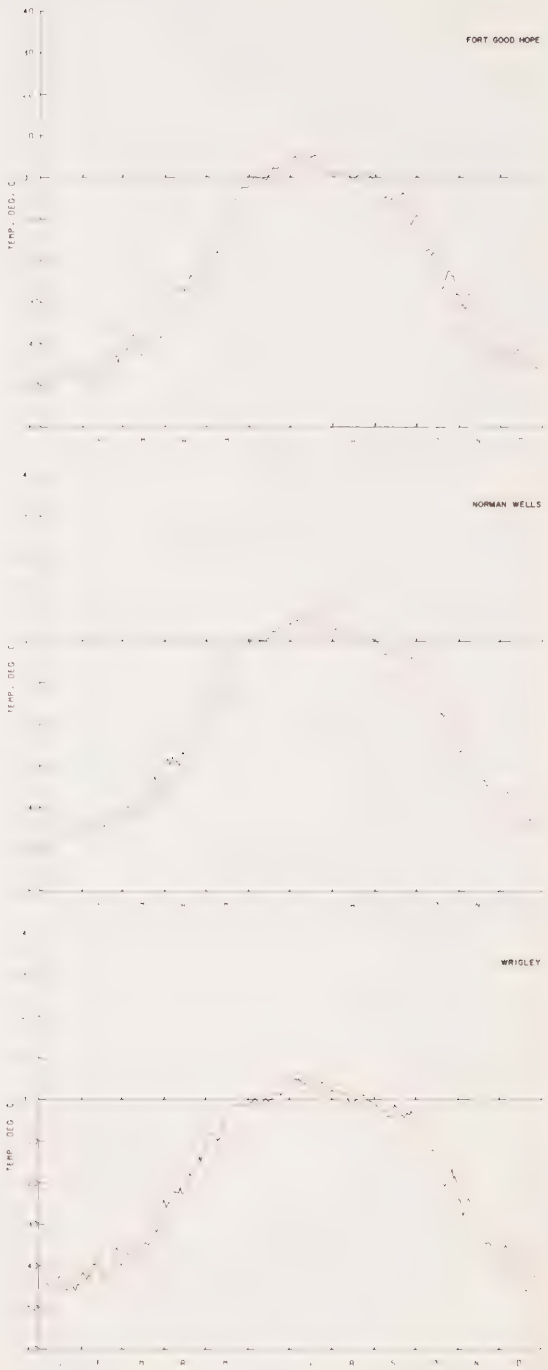
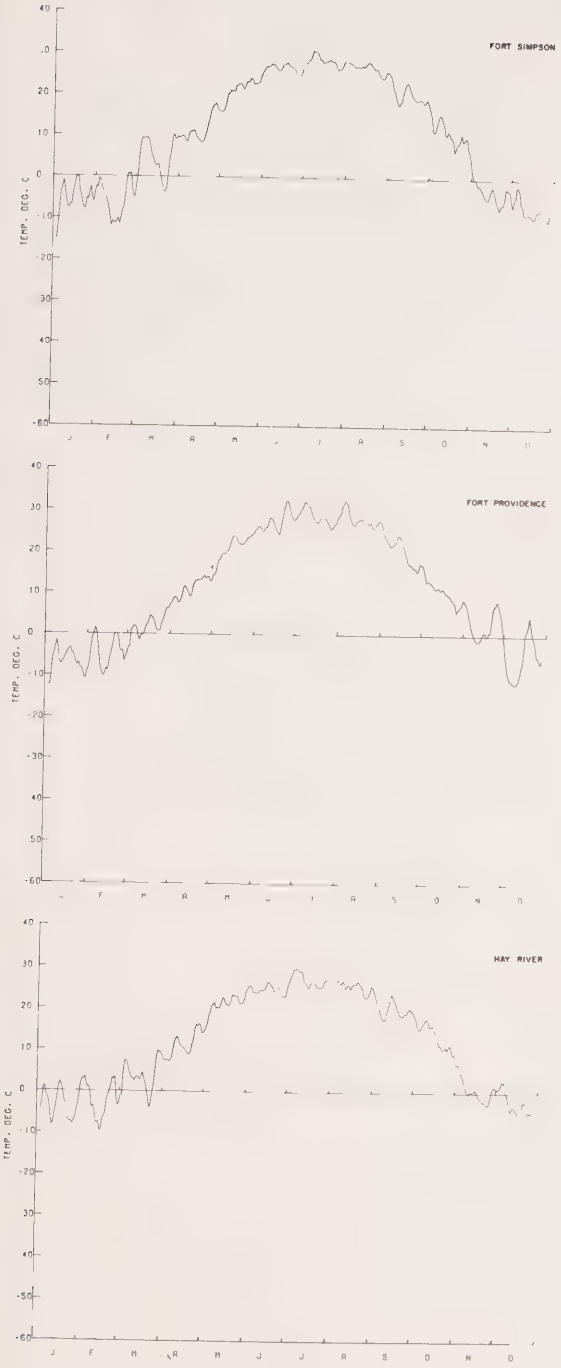


Figure 6a.

Five day moving averages of maximum temperatures (1957-67).

Five day moving averages of minimum temperatures (1957-67).



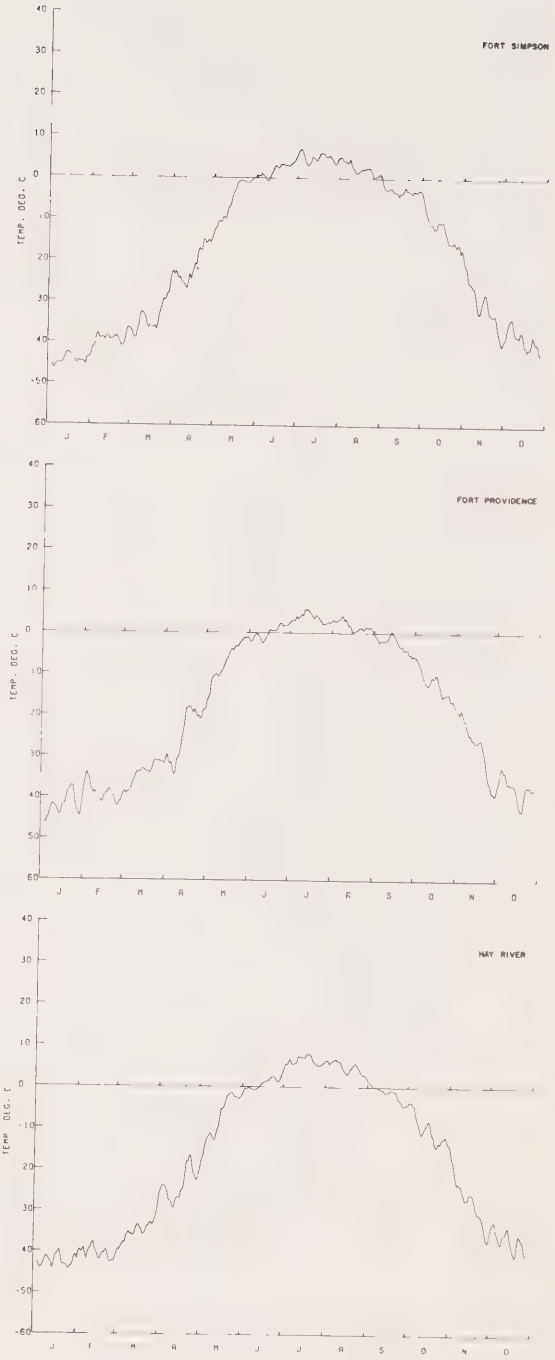


Figure 6b.

Five day moving averages of maximum temperatures (1957-67).

Five day moving averages of minimum temperatures (1957-67).

3. Frequency of extreme events is low. They occur mainly during the summer and are not usually associated with thunderstorms.

4. A sample of selected stations, analysed for the duration of precipitation, suggests that precipitation of relatively high intensity is not necessarily limited to extreme events. Six-hour falls can occur on days with more than 6 mm of precipitation as well as on days with more than 15 mm of precipitation.

5. An analysis suggests that the five day moving averages of maximum daily temperatures averaged over a ten-year period are close to freezing from October to May in the central part of the region, and from October to June further north. On occasions when the maximum is above 0° and the minimum below this value, working conditions could be adverse as the surface may be subject to periodic freeze and thaw.

It is suggested that future work should include:

(a) A study of selected individual rainfalls in summer to obtain intensity rates over short periods.

(b) A close investigation of temperatures in spring and autumn to evaluate freeze and thaw cycles.

(c) Using the precipitation classification outlined in this report, an examination of the weather conditions associated with precipitation in different classes with particular reference to freezing rain, frost, fog and blowing snow.

ACKNOWLEDGEMENTS

I would like to thank Michael Boakes for the preparation of the computer programmes and graphs.

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NICHOLSON PENINSULA

69°54'N,128°58'W, Elev. 27 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurences Over 10 Years	14	10	18	21	19	22	54	87	68	44	17	14
Total ppt. in mm Over 10 Years	24	14	26	38	32	103	215	320	164	96	32	25
Class 2												
% of total Occurrences	100.00	100.00	100.00	100.00	100.00	81.82	77.78	75.86	91.18	90.91	94.12	100.00
% of total ppt.	100.00	100.00	100.00	100.00	100.00	42.81	41.78	34.68	63.98	70.90	74.80	100.00
Avg. ppt. in class	2	1	1	2	2	25	2	2	2	2	2	2
Class 3												
% of total Occurrences						9.29	12.96	14.94	2.94	9.09	5.00	
% of total ppt.						20.45	22.25	27.70	9.01	29.10	25.20	
Avg. ppt. in class						8	7	7	7	7	8	
Class 4												
% of total Occurrences						4.55	7.41	5.75	5.88			
% of total ppt.						13.74	22.96	19.29	27.02			
Avg. ppt. in class						11	12	12	12			
Class 5 & Higher												
% of total Occurrences						4.55	1.85	3.45				
% of total ppt.						23.00	13.02	18.33				
Avg. ppt. in class						18	28	20				

TUKTOYAKTUK

69°27'N, 132°59'W.

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 years	27	32	24	35	28	37	78	79	67	61	26	29
Total ppt. in mm Over 10 Years	28	54	30	54	85	94	205	284	245	124	43	71
Class 2												
% of total Occurrences	100.00	93.75	95.83	97.14	89.29	86.49	78.12	77.22	89.55	95.08	96.15	89.66
% of total ppt.	100.00	72.77	79.17	83.41	61.45	60.27	36.58	29.72	59.24	85.42	85.38	73.02
Avg. ppt. in class	1	1	1	1	2	2	1	1	1	2	2	2
Class 3												
% of total Occurrences		6.25	4.17	2.86	7.14	10.81	16.67	13.92	5.97	4.92	3.85	10.34
% of total ppt.		27.23	20.83	16.59	20.73	27.03	39.67	27.52	16.83	14.58	14.62	25.98
Avg. ppt. in class		7	6	8	7	12	8	8	7	6	6	6
Class 4												
% of total Occurrences					3.57	2.70	3.85	3.80	4.48			
% of total ppt.					17.82	12.70	16.02	11.09	23.93			
Avg. ppt. in class					12	12	14	11	12			
Class 5 & Higher												
% of total Occurrences							1.28	5.07				
% of total ppt.							7.72	31.66				
Avg. ppt. in class							20	24				

Precipitation Analysis

Table 1 (cont'd)

AKLAVIK

68°14'N135°00'W, Elev. 9 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	90	80	82	50	47	54	88	105	98	130	100	92
Total ppt. in mm Over 10 Years	135	79	84	48	58	131	262	342	262	262	122	107
Class 2												
% of total Occurrences	94.44	97.50	97.56	100.00	95.74	83.33	85.23	82.86	86.73	90.77	98.00	98.91
% of total ppt.	67.29	82.05	85.15	100.00	71.18	50.10	42.64	45.35	56.88	63.79	85.39	94.46
Avg. ppt. in class	1	1	1	1	1	2	2	2	2	2	1	1
Class 3												
% of total Occurrences	3.33	2.50	2.44		2.13	14.81	6.82	10.48	11.22	7.69	2.00	1.09
% of total ppt.	13.91	17.95	14.85		9.17	41.20	16.18	22.75	32.85	26.60	14.61	5.54
Avg. ppt. in class	6	7	6		5	7	7	7	8	7	9	6
Class 4												
% of total Occurrences	2.22				2.13	1.85	5.68	2.86	2.04	1.54		
% of total ppt.	18.80				19.65	8.70	25.87	10.93	10.27	9.61		
Avg. ppt. in class	13				11	11	14	12	14	13		
Class 5												
% of total Occurrences							2.28	3.81				
% of total ppt.							15.31	20.97				
Avg. ppt. in class							20	18				

Table 1 (cont'd)

INUVIK

68°18'N,133°29'W, Elev. 61 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	122	109	122	104	84	69	102	96	102	150	115	154
Total ppt. in mm Over 10 Years	187	126	152	147	210	228	361	536	181	320	151	207
Class 2												
% of total Occurrences	94.26	99.08	98.37	96.15	85.71	79.71	72.00	66.34	91.18	90.67	96.52	96.10
% of total ppt.	71.68	89.11	89.50	73.40	44.44	39.29	29.11	22.42	58.96	68.10	78.96	79.90
Avg. ppt. in class	1	1	1	5	1	1	1	1	1	1	1	1
Class 3												
% of total Occurrences	4.92		0.81	2.88	9.52	14.49	16.00	25.74	6.86	8.67	3.48	3.90
% of total ppt.	22.76		3.50	14.51	25.24	34.60	28.28	38.15	28.95	27.43	21.04	20.10
Avg. ppt. in class	7		5	7	7	8	7	8	8	7	8	7
Class 4												
% of total Occurrences	0.82	0.92	0.81		2.38	2.90	9.00	1.98	1.96	0.67		
% of total ppt.	5.56	10.89	7.00		10.63	9.71	27.39	4.27	12.08	4.47		
Avg. ppt. in class	10	14	11		11	11	12	11	12	14		
Class 5 & Higher												
% of total Occurrences				0.96	2.38	2.90	3.00	5.94				
% of total ppt.				12.09	19.68	16.41	15.22	35.17				
Avg. ppt. in class				18	21	19	19	32				

Precipitation Analysis

Table 1 (cont'd)

FORT GOOD HOPE

66°15'N,128°38'W, Elev. 76 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	113	113	114	73	67	90	130	105	115	144	124	140
Total ppt. in mm Over 10 Years	224	185	167	155	171	460	510	835	393	355	262	307
Class 2												
% of total Occurrences	92.04	97.30	93.86	91.78	88.06	64.44	74.79	73.08	74.29	89.58	92.74	92.14
% of total ppt.	73.19	85.73	65.25	70.92	55.64	24.46	28.55	30.30	33.27	64.23	73.06	70.99
Avg. ppt. in class	2	2	1	2	1	2	1	2	2	2	2	2
Class 3												
% of total Occurrences	7.08	1.80	5.26	5.48	7.46	0.53	16.81	13.85	15.24	8.33	6.45	7.14
% of total ppt.	22.17	6.86	23.67	16.05	22.55	26.67	29.80	21.78	28.42	24.03	22.29	24.79
Avg. ppt. in class	6	6	7	7	8	7	8	7	7	7	7	8
Class 4												
% of total Occurrences	0.88	0.90		2.74	4.48	4.64	4.20	8.46	7.62	1.39	0.81	0.71
% of total ppt.	4.64	7.41		13.03	21.81	11.21	11.76	23.83	24.94	7.01	4.65	4.21
Avg. ppt. in class	10	14		12	12	13	12	13	12	12	12	13
Class 5 & Higher												
% of total Occurrences			0.88			4.44	4.20	4.62	2.86	0.69		
% of total ppt.			11.08			25.07	29.89	24.09	13.37	4.72		
Avg. ppt. in class			19			29	34	26	18	17		

Precipitation Analysis

Table 1 (cont'd)

NORMAN WELLS

65°18'N, 126°51'W, Elev. 64 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	137	127	114	96	66	90	134	116	106	149	139	134
Total ppt. in mm Over 10 Years	274	223	155	163	155	356	576	560	319	300	219	219
Class 2												
% of total Occurrences	91.97	92.80	94.78	92.71	90.91	73.33	76.87	75.86	83.96	89.93	95.68	94.78
% of total ppt.	64.56	66.67	75.65	72.64	68.57	28.62	29.89	29.26	46.22	58.05	76.94	73.00
Avg. ppt. in class	2	1	1	1	2	2	2	2	2	1	1	1
Class 3												
% of total Occurrences	5.84	5.60	5.22	7.29	9.09	13.33	9.70	13.79	11.32	8.05	3.60	3.73
% of total ppt.	20.50	31.58	24.35	27.36	31.43	25.34	17.15	19.65	26.29	29.15	15.53	14.37
Avg. ppt. in class	7	7	6	6	7	8	8	7	7	7	7	6
Class 4												
% of total Occurrences	2.19	1.60				8.89	7.46	2.59	0.94	1.34		0.75
% of total ppt.	14.94	11.76				26.77	22.80	6.31	3.98	7.54		4.87
Avg. ppt. in class	14	13				12	14	12	13	11		11
Class 5 & Higher												
% of total Occurrences						4.44	5.97	7.77	3.97	0.67	0.72	0.75
% of total ppt.						20.27	30.15	44.78	23.50	5.25	7.53	7.76
Avg. ppt. in class						18	24	28	20	16	17	17

Precipitation Analysis

Table 1 (Cont'd)

WRIGLEY

63°12'N123°25'W, Elev. 155 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	86	83	101	70	65	78	91	66	82	107	106	106
Total ppt. in mm Over 10 Years	197	133	106	161	208	222	345	282	317	293	191	191
Class 2												
% of total Occurrences	89.53	96.39	97.03	85.71	83.08	74.36	70.33	66.67	80.00	83.18	95.28	90.57
% of total ppt.	57.66	85.66	83.91	41.32	32.97	32.04	7.96	14.73	32.51	46.27	76.00	59.20
Avg. ppt. in class	2	2	1	1	1	2	1	1	2	3	1	1
Class 3												
% of total Occurrences	8.14	3.61	2.97	8.57	6.15	17.95	15.38	18.18	8.75	12.15	3.77	8.49
% of total ppt.	26.77	14.34	16.09	26.18	13.92	36.75	30.43	28.93	17.09	32.84	17.33	32.80
Avg. ppt. in class	8	6	6	7	7	7	8	9	8	7	8	7
Class 4												
% of total Occurrences	1.16			4.29	4.62	3.85	8.79	10.61	5.00	3.74	0.94	0.94
% of total ppt.	5.35			19.87	17.58	11.73	28.00	28.66	15.74	15.60	6.67	8.00
Avg. ppt. in class	11			11	12	11	12	12	13	11	13	15
Class 5 & Higher												
% of total Occurrences	1.16			1.43	6.16	3.85	5.50	4.55	6.25	0.93		
% of total ppt.	10.21			12.62	35.53	19.48	23.60	27.67	34.67	5.29		
Avg. ppt. in class	21			20	20	18	23	23	23	16		

Precipitation Analysis

Table 1 (Cont'd)

FORT SIMPSON

61°52'121°35'W

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	121	119	121	79	65	95	100	87	91	106	122	138
Total ppt. in mm Over 10 Years	254	155	56	141	221	427	630	397	376	324	313	234
Class 2												
% of total Occurrences	90.08	97.48	95.04	93.67	76.92	74.74	67.89	75.86	69.23	81.13	88.52	93.48
% of total ppt.	54.95	86.11	80.10	69.55	34.29	29.71	21.66	28.45	29.03	38.84	58.35	65.18
Avg. ppt. in class	1	1	2	1	2	2	2	2	2	1	2	1
Class 3												
% of total Occurrences	7.44	2.52	4.96	5.06	18.46	14.74	13.76	11.49	20.88	11.32	5.74	5.80
% of total ppt.	24.88	13.89	19.90	19.28	36.71	22.99	16.86	17.77	35.25	26.23	14.75	26.57
Avg. ppt. in class	8	8	8	8	8	8	8	8	8	8	8	8
Class 4												
% of total Occurrences	1.65				1.54	4.21	9.17	6.90	7.69	5.66	4.92	
% of total ppt.	10.99				5.06	12.18	19.28	18.35	22.89	24.04	21.64	
Avg. ppt. in class	13				11	13	13	13	13	13	13	
Class 5 & Higher												
% of total Occurrences	0.83			0.62	3.08	6.32	9.17	5.75	2.20	1.89	0.82	0.72
% of total ppt.	9.19			1.27	23.93	35.11	42.20	35.42	12.83	10.88	5.27	8.24
Avg. ppt. in class	24			30	26	25	32	26	26	18	18	20

Precipitation Analysis

Table 1 (cont'd)

FORT PROVIDENCE

61°20'N, 117°40'W, Elev. 159 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	95	75	88	54	44	57	81	65	77	69	79	111
Total ppt. in mm Over 10 Years	143	125	202	106	106	225	398	301	262	226	218	227
Class 2												
% of total Occurrences	95.79	94.67	89.77	92.59	87.82	68.42	69.14	40.77	41.43	79.71	87.34	94.59
% of total ppt.	80.28	78.00	52.89	64.66	42.52	34.28	19.35	27.62	31.98	43.71	46.32	74.44
Avg. ppt. in class	1	1	1	1	1	1	1	1	1	1	2	1
Class 3												
% of total Occurrences	4.21	5.33	2.27	5.56	15.91	26.32	17.28	18.46	23.38	13.04	8.86	2.70
% of total ppt.	19.72	22.00	10.93	24.52	43.82	46.27	25.86	30.07	49.52	24.72	24.85	10.65
Avg. ppt. in class	8	8	2	8	8	8	8	8	8	8	8	8
Class 4												
% of total Occurrences			2.27	1.85		3.51	6.17	3.08	3.90	5.80	1.27	2.70
% of total ppt.			10.93	10.82		12.50	16.48	7.77	12.40	24.16	5.25	14.91
Avg. ppt. in class			12	12		14	13	12	11	14	11	11
Class 5 & Higher												
% of total Occurrences			2.27		2.27	1.75	7.41	7.70	1.30	1.45	2.54	
% of total ppt.			18.09		13.67	6.90	38.41	34.55	6.10	7.42	23.57	
Avg. ppt. in class			18		14	15	25	20	16	17	25	

Precipitation Analysis

Table 1 (Cont'd)

YELLOWKNIFE

62°28'114°27'W, Elev. 208 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	122	116	112	73	49	57	102	87	105	132	184	140
Total ppt. in mm Over 10 Years	225	135	163	123	155	197	402	353	308	364	310	211
Class 2												
% of total Occurrences	96.72	99.12	94.64	91.78	85.71	77.19	81.37	77.01	80.00	83.33	95.11	95.00
% of total ppt.	82.05	96.05	75.78	63.71	35.40	32.22	40.67	25.65	33.61	39.92	78.21	77.40
Avg. ppt. in class	1	1	1	1	1	2	2	1	1	1	2	1
Class 3												
% of total Occurrences	3.28	0.88	5.36	6.85	6.12	14.04	10.78	10.34	12.38	9.85	4.35	4.29
% of total ppt.	17.95	3.95	24.22	25.36	13.38	29.77	21.70	18.16	28.25	28.54	18.10	17.19
Avg. ppt. in class	8	5	7	6	7	7	8	8	7	8	7	6
Class 4												
% of total Occurrences				1.37	4.08	3.51	2.94	6.90	4.76	6.06	0.54	0.71
% of total ppt.				10.93	15.50	17.91	8.48	19.81	19.19	27.22	3.69	5.41
Avg. ppt. in class				13	12	18	11	12	12	12	12	12
Class 5 & Higher												
% of total Occurrences							3.92	5.75	2.85	0.76		
% of total ppt.							29.16	36.38	18.95	4.33		
Avg. ppt. in class							56	75	40	16		

Precipitation Analysis

Table 1 (cont'd)

HAY RIVER

60°51'115°57'W, Elev. 162 meters

	J	F	M	A	M	J	Jy	A	S	O	N	D
Total No. of Occurrences Over 10 Years	119	113	103	58	52	82	101	94	92	112	156	135
Total ppt. in mm Over 10 Years	272	237	80	124	146	291	669	311	462	444	514	328
Class 2												
% of total Occurrences	89.92	89.38	90.99	91.38	82.69	80.49	64.36	80.85	70.65	75.00	83.78	88.89
% of total ppt.	62.62	56.15	65.93	58.57	44.95	36.59	16.77	42.53	30.31	32.11	39.88	55.19
Avg. ppt. in class	23	1	1	1	1	1	2	2	2	2	2	2
Class 3												
% of total Occurrences	9.24	7.08	7.21	3.45	15.38	12.20	14.85	15.96	21.74	16.96	8.11	7.41
% of total ppt.	31.87	23.21	24.54	12.04	41.11	29.43	15.90	36.00	34.10	29.36	17.32	20.08
Avg. ppt. in class	8	7	6	8	8	9	7	8	8	7	8	7
Class 4												
% of total Occurrences	0.84	3.54	1.80	5.17		3.66	6.93	1.06	4.35	4.46	4.05	1.48
% of total ppt.	5.51	20.64	10.43	29.39		12.49	13.89	5.47	11.33	15.46	14.02	7.60
Avg. ppt. in class	15	12	11	12		12	13	12	13	14	12	12
Class 5 & Higher												
% of total Occurrences					1.92	2.66	13.86	2.12	3.26	3.57	4.06	2.22
% of total ppt.					13.94	21.48	53.43	17.71	24.26	23.07	28.78	17.14
Avg. ppt. in class					20	23	23	26	36	18	23	19

Precipitation Analysis

Table 1 (cont'd)

Nicholson	±32	
Tuktoyaktuk	±40	Northern
Inuvik	±55	Mackenzie
Aklavik	±54	
Fort Good Hope	±103	
Norman Wells	±58	Central
Wrigley	±118	Mackenzie
Fort Simpson	±117	
Fort Providence	±77	Southern
Hay River	±80	Mackenzie
Yellowknife	±38	

All values are in millimetres

Inter-sequential Variability of Annual Precipitation

in the Mackenzie Valley region

Table 2

	Nicholson				Tuktoyaktuk				Inuvik				Aklavik			
	June	July	Aug.	Sept.	June	July	Aug.	Sept.	June	July	Aug.	Sept.	June	July	Aug.	Sept.
1957						1										
1958																
1959		1													2	
1960																1
1961							2									2
1962	1		1				1			2		1				
1963			1								1					
1964			1								1					
1965							1				1	1				
1966																
1967																

	Fort Good Hope				Norman Wells				Wrigley			
	June	July	Aug.	Sept.	June	July	Aug.	Sept.	June	July	Aug.	Sept.
1957			1			2	2	1				
1958										1		
1959		2		1				2				2
1960							2				1	1
1961	2			1	2	2	3					
1962					1	1						1
1963			1		1		1		2	1	2	
1964			1			1				3		1
1965	1		1			2			1			
1966							1	1				
1967				1								

	Fort Simpson				Fort Providence*				Hay River				Yellowknife			
	June	July	Aug.	Sept.	June	July	Aug.	Sept.	June	July	Aug.	Sept.	June	July	Aug.	Sept.
1957	1	3				2				2			1	1		1
1958		1	1				3	1		1	1				2	
1959				1		2	1			2				2	1	1
1960		2	1			1				1	1				1	
1961	1		1						1	2				1		
1962	1	1	1						1	1			1			
1963	1	1								2				1		
1964	1		1	1								2				1
1965	1	1								1						
1966		1							1	1		1				
1967																

* Data for this station was available for the period 1952-62, as a result of which listings for the period 1962-67 are absent.

Number of extreme event (>15mm) precipitation occurrences over a 24-hour period for 1st order and climatological stations during the summer months along the Mackenzie valley.

Table 3

	No. of Snowfalls	Total Amount in mm	No. of Rainfalls	Total Amount in mm	Occurrences % Snow	Occurrences % Rain
Nicholson Peninsula	-	-	5	105	-	100
Tuktoyaktuk	-	-	5	115	-	100
Inuvik	2	39	12	307	14	86
Aklavik	-	-	6	91	-	100
Fort Good Hope	1	19	19	475	5	95
Norman Wells	4	66	24	580	7	93
Wrigley	2	41	21	282	9	91
Fort Simpson	4	76	27	674	13	87
Fort Providence	2	37	17	390	2	98
Hay River	12	333	23	610	34	66
Yellowknife	1	16	17	393	6	94

List of Precipitation Occurrences Greater Than 15mm per day

Over 10 Years (1957-67)

Table 4

Inuvik - N. Mackenzie	Hours	0600-1200	1200-1800	1800-2400	2400-0600	Σ
August 17, 1965		1	23	0	3	26
August 31, 1962		2	9	16	3	29
July 28, 1962		6	6	1	0	13
June 6, 1963		10	0	0	0	10
June 23, 1967		T	8	1	0	9
Norman Wells - C. Mackenzie						
July 19, 1964		21	T	0	0	31
August 15, 1960		T	3	8	10	21
July 3, 1957		1	6	3	3	13
June 6, 1958		2	4	4	1	11
July 31, 1958		3	4	2	T	9
Fort Simpson - S. Mackenzie						
July 8, 1960		13	21	19	8	60
July 20, 1966		22	6	0	0	28
July 9, 1960		7	2	4	T	13
June 2, 1962		1	5	6	0	12
July 6, 1963		0	0	0	8	8

T - trace

Six Hourly Precipitation Amounts at Sample Stations

all values are in millimetres

Table 5

STUDY OF
GEOMORPHIC AND HYDROLOGIC CHARACTERISTICS
of
MACKENZIE RIVER TRIBUTARY BASINS

by

T. Thakur and A.G.F. Lindeijer

Technical Report 14 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

Environmental-Social Program
Northern Pipelines

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ABSTRACT

In this report the geomorphic character of Mackenzie River tributary watersheds is described by a number of parameters related to linear, areal, and relief aspects of the channel network obtained from the available maps. The hydrologic characteristics selected define the expected peak flows and are estimated by standard flood frequency methods for gauged watersheds. Multiple regression procedures are used to develop preliminary prediction equations relating geomorphic and hydrologic characteristics. The equations are used to estimate peak flows for ungauged basins. On the basis of initial results the east side of the Mackenzie River seems to offer a safer route for pipelines than the west side.

NOTATION

Morphology

AVE = Average elevation (ft)
BF = Bifurcation ratio
CCM = Constant of channel maintenance (ft^2)
CLA = Latitude (degrees)
CLO = Longitude (degrees)
CP = Basin perimeter (miles)
CSIN = Sinuosity
DA = Drainage area ($miles^2$)
DD = Drainage density ($miles/miles^2$)
F = Stream frequency
H = Basin relief (ft)
HCK = Hypsometric coefficient
HYI = Hypsometric integral
LB = Basin length (miles)
MAE = Maximum elevation (ft)
MCL = Main channel length (miles)
MEE = Mean elevation (ft)
MIE = Minimum elevation (ft)
PAA = Percent area above average elevation
PAE1 = Percent area at elevation 0-2000 ft
PAE2 = Percent area at elevation 2000-4000 ft
PAE3 = Percent area at elevation 4000-6000 ft
PAE4 = Percent area at elevation 6000 ft and over
PF = Percent area of basin covered by forest
PGL = Percent area of basin covered by glacier
PLSW = Percent area of basin covered by lake and swamp
RA = Area ratio
RB = Weighted mean bifurcation ratio
RC = Circulatory ratio
RE = Elongation ratio
RH = Relief ratio x 100
RL = Length ratio
SLOP = Slope factor (ft/mile)

Hydrology

MAF = Mean annual flow ($ft^3\ s^{-1}\ miles^{-2}$)
MAFF = Mean annual flood with 50-yr. return period ($ft^3\ s^{-1}\ miles^{-2}$)
MAFH = Mean annual flood with 100-yr. return period ($ft^3\ s^{-1}\ miles^{-2}$)
T = Mean flood with 2.33-yr. return period ($ft^3\ s^{-1}\ miles^{-2}$)

INTRODUCTION

General nature and scope of study

The proposed northern pipelines must cross several large and many small streams. Besides major crossings of the Peel, Mackenzie and possibly the Liard rivers, pipelines must cross many of the large tributaries of these rivers.

Pipelines may be buried or elevated at stream crossings depending upon channel approaches, banks and other fluvial and hydrologic stream characteristics. The safety of the pipelines at stream crossings could be jeopardized by ice jamming, flooding and scour. Supporting structures for river crossings could be undermined causing pipe failure. Flooding may cause large-scale erosion of cut banks, streambed scouring and shifting of channels that threaten the safety of pipelines. It is necessary, therefore, to obtain detailed information on the hydrologic characteristics of watersheds crossed by the pipelines and on the factors affecting them.

The volume of flood flow and the maximum flood discharge are regarded as principal hydrologic characteristics used for design purposes. The long-term study of floods provides a method of estimating future occurrences. However, in the case of the Mackenzie River tributaries, recorded hydrologic data are very inadequate for computation and forecasting of floods.

Available data are limited and consist mostly of short-term records. Several authors have written about different aspects of the study area (Figure 1). Bird (1967) gave a detailed account of physiographic features and climatic patterns for arctic Canada. Mackay (1958, 1963, 1963a, 1966, 1966a, 1966b, 1970, 1971) wrote extensively about landforms and processes in the area and Brown' (1970) detailed permafrost distribution. MacKay (1965, 1966, 1967) gave an account of runoff patterns and river ice break-up and freeze-up phenomena on the Mackenzie River. The Shawinigan Engineering Company Limited (1970) carried out a detailed hydrometric planning study for western and northern Canada under a contract from the Water Survey of Canada.

Work on a morphometric analysis of Mackenzie tributary watersheds began under the Environmental-Social Program of Northern Pipelines in the summer of 1971. J. Jasper assisted in the initial phase of data collection and has presented some results for headwater tributaries in the Liard - Mackenzie River Basins (Jasper, 1972). The procedure for data collection and analysis has been summarized by Strahler (1964), Thomas and Benson (1970), Gladwell (1970), and Melton (1958).

Here, an attempt is made to estimate peak flows by indirect methods related to geomorphic or physiographic features of the basins. The results presented are introductory in nature, but in the absence of any other reliable data sources, the method provides an estimation of hydrologic characteristics which could be used for design purposes. However, attempts are being made to improve mathematical techniques and procedures applicable to the available data.

Objectives

The current investigation examines the relationship between peak runoff characteristics and geomorphic or morphometric factors in Mackenzie tributary watersheds with the following specific objectives:

1) To describe basic morphometry of Mackenzie River tributary watersheds from available topographic maps by defining geomorphic characteristics related to channel network and topography;

2) To evaluate all the available hydrologic data and to select and define suitable hydrologic parameters of peak flow;

3) To develop optimal mathematical equations defining the relationship between geomorphic characteristics and hydrologic characteristics of the gauged watersheds;

4) To apply the equations to ungauged watersheds with defined morphometric characteristics;

5) To develop alternative sets of equations for the basins with distinctly different physiographic and regional features; and

6) To identify geomorphic characteristics affecting pipeline construction on the basis of results from the study.

METHODS AND SOURCES OF DATA

Morphometric analysis

The geomorphic character of drainage basins may be described using numerous measurable parameters. These properties can be classified by the following criteria:

1) Length or geometric properties of the drainage net

2) Shape or area of the drainage basin; and

3) Relief or hypsometric aspects of the drainage basin.

Definitions of these morphologic parameters and their interrelationships are described in the following sections. A case study of Frances River Basin, a tributary of the Liard (Fig. 2) is used as an example with illustrations of all the parameters determined. A similar procedure has been followed in analysing every watershed in the study area.

Frances River Basin has been divided into 22 subbasins as shown in Figure 2. Gauging Station 10AB001 measures the combined flow of 21 subbasins. The river then flows through subbasin 22 before it joins the Liard River. The morphometric parameters have been determined for the entire watershed including subbasin 22.

General procedure

The study area is divided into primary drainage basins using

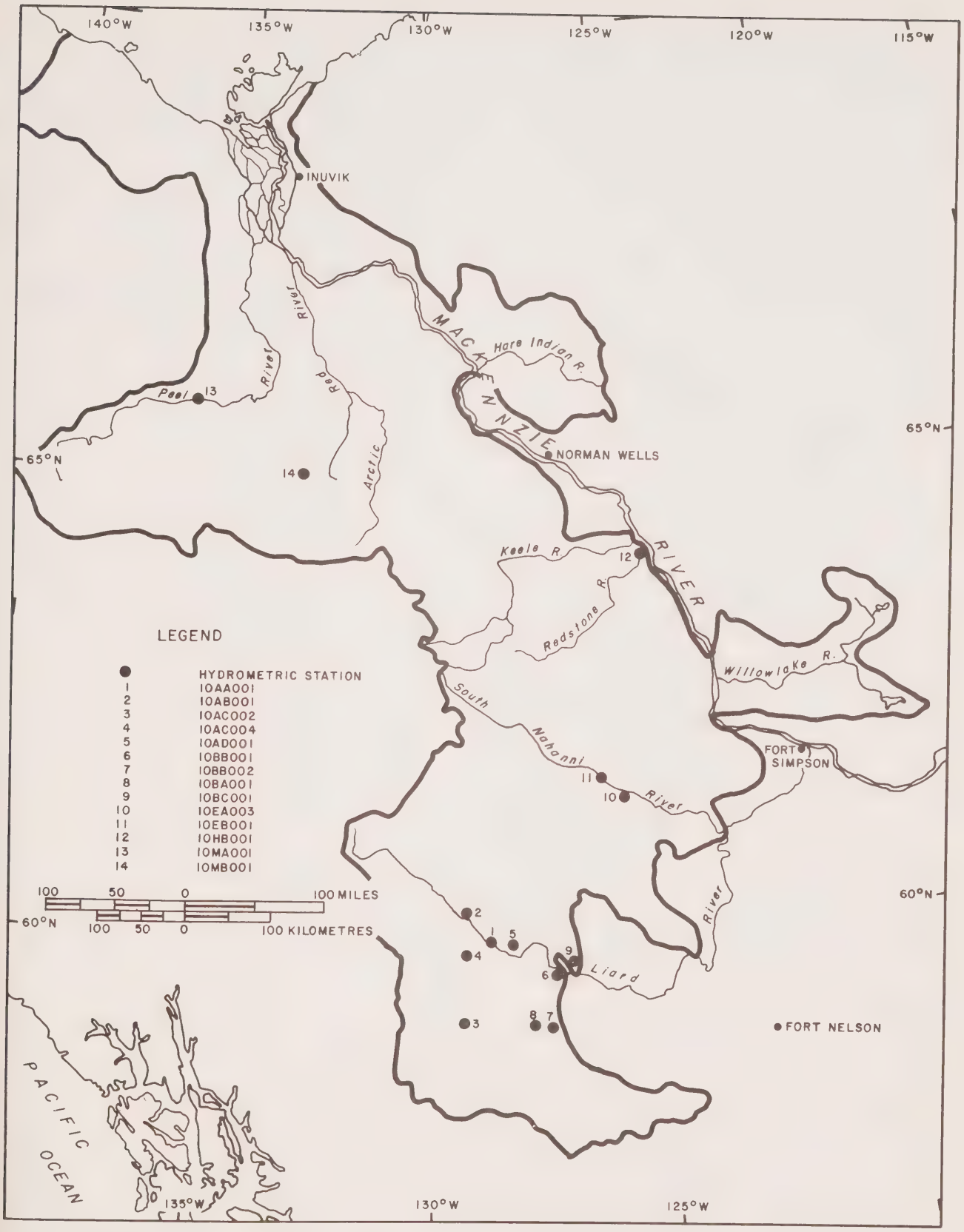


Figure 1. Study area and location of hydrometric stations in the Mackenzie River Basin, NWT

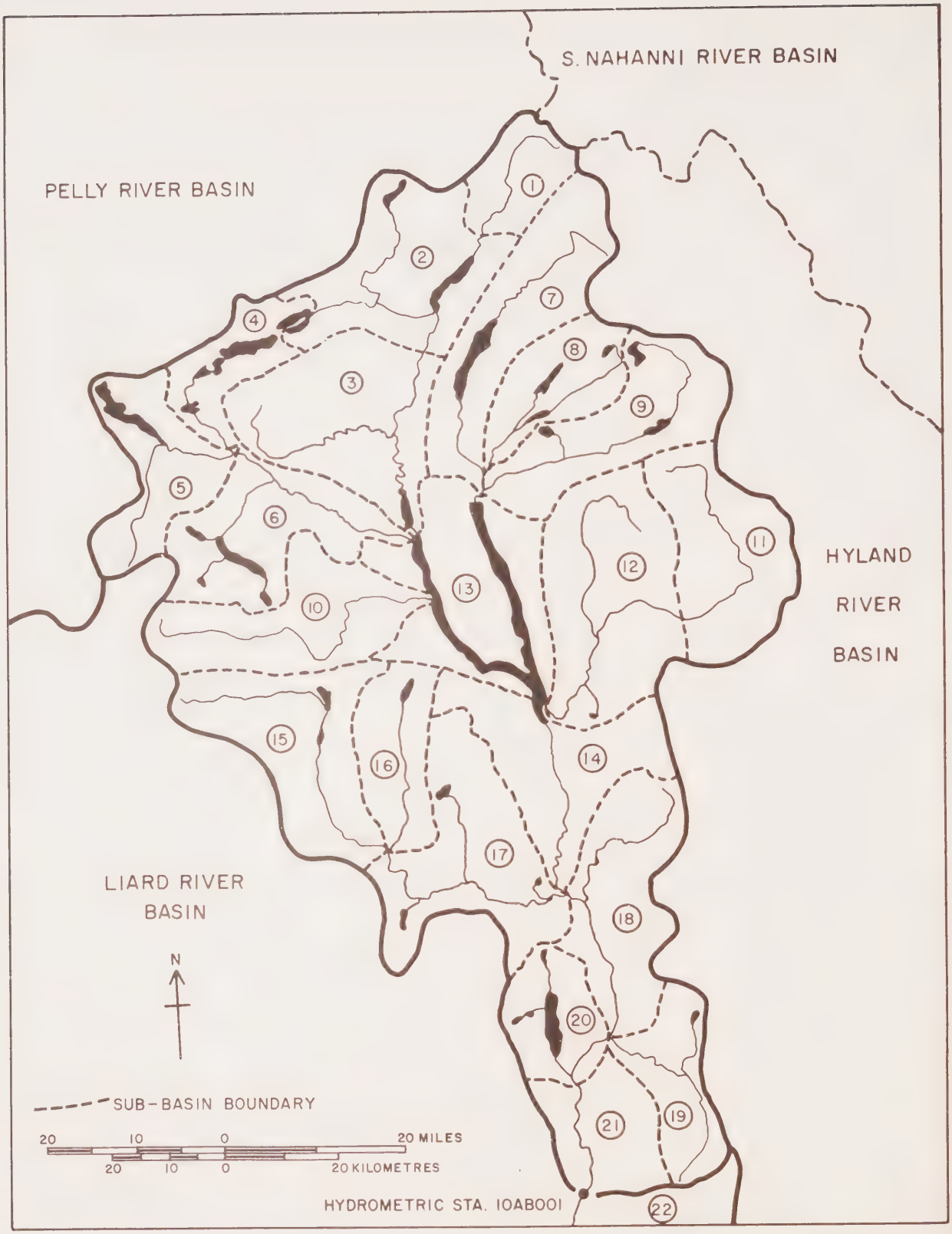


Figure 2. Frances River Basin outline, case study.

procedures adopted by the Water Survey of Canada. Perimeters of each drainage basin are outlined on topographic maps at a scale of 1:250,000, and each primary basin is further subdivided into smaller units to facilitate data collection (Fig. 2). The parameters of these smaller units are recombined to give results for the primary drainage basins. No field checking or large-scale air photographic verification was possible in the limited time available.

Data collection.

The subbasin units outlined have an average area of approximately 300-400 miles^2. For each subbasin the following data were obtained directly from the maps:

1) Strahler's stream numbers,

2) Length of streams of each order,

3) Drainage area of streams of each order,

4) Perimeter length, and

5) Basin surface-cover area.

The following features were obtained for the entire primary basin:

1) Main channel length,

2) Area-length relationship,

3) Length-altitude relationship,

4) Hypsometry (area-altitude relationship), and

5) Basin drainage area.

Instruments and methods.

Linear measurements were obtained with an opisometer or chartometer. Each measurement was repeated twice and the mean value was used for computation. The accuracy of the values determined is in the order of ±3%.

A compensating polar planimeter was used in all areal measurements except those for surface cover and hypsometry. Accuracies for repeated measurements of drainage basin area, area drained by streams of each order, and drainage area versus channel length are found to be in the order of 2 to 3 percent. Percentage of surface cover in forest, lake, swamp and glacier has been determined since these features affect runoff intensity.

The fine detail of these patterns necessitated a method of area measurement more accurate than the planimeter. This problem was solved by using a random dot overlay. With a map scale of 1:250,000, this method claims an accuracy of 97.27%. The sums obtained for each surface-cover features were compiled for the watershed, converted first into square miles and then into percentages of total basin area.

Hypsometry is the basin area-altitude relationship found by measuring the drainage area within each contour interval, and summed to give a cumulative frequency curve. The integral of this area-altitude curve has been suggested as an indicator of stage of basin geologic development (Strahler, 1952). Haan and Johnson (1966) suggested a method for fast intra-contour area determination based on a random sampling technique. Results obtained (Jasper,1972) using this method indicate that the curves generated are as good as those obtained by using Polar planimeter measurements.

Data presentation.

The following relationships are presented graphically for each primary watershed in the study area:

1) Stream order vs number of streams,

2) Stream order vs stream length,

3) Stream order vs drainage area,

4) Perimeter vs drainage area,

5) Distance along main channel (from the highest point in the basin) vs drainage area,

6) Length-altitude profile, and

7) Area-altitude profile.

The case study (Frances River basin) results are included in this report and tables and figures are used to explain the defined morphometric terms in the following section. The mathematical calculations performed to determine the basin parameters are indicated in the following section.

Definitions of morphometric characteristics.

Longitude (CLO) and latitude (CLA) of a basin serve to locate the centre of gravity of the basins and were obtained according to Gladwell (1970).

Stream order numbers, when determined from map analysis rather than field studies, have doubtful validity, due to the ephemeral nature of some streams and the scale of the maps used. This inconsistency is recognized: "usefulness of stream order system depends on the premise that, on the average, if a sufficiently large sample is treated, order number tends to be proportional to the size of the contributing watershed, to channel dimensions and to stream discharge at that place in the system" (Strahler, 1964).

Strahler's method of numbering proceeds from the uppermost tributaries, termed first-order streams. Where two first-order streams come together, they form a second-order stream; two second-order streams form a third-order stream and so on. After the order numbers have been assigned to the drainage network elements, the segments of each order are counted to

yield the number of streams of given order (N). Table 1 shows results of stream-order analysis for Frances River Basin, and Figure 3 is a plot of the logarithm of the number of streams against stream order. The network shows a linear relationship.

Bifurcation ratio, according to Horton (1945) is a ratio of the total number of streams or order N_u to that of the next higher order N_{u+1}

$$BF = \frac{N_u}{N_{u+1}}$$

The bifurcation ratio tends to be constant from one order to the next following Horton's law of stream numbers (1945). To eliminate random irregularities which exist between bifurcation ratios of successive stream orders, a term, weighted mean bifurcation ratio, (RB) is derived by multiplying bifurcation ratios and then finding the mean of the sum of the values. For the purpose of current analysis, only the weighted mean bifurcation ratios are taken into consideration.

Stream length (L_u) is the total length of u order streams in miles. Stream length was measured with a chartometer directly from the map. $\bar{L}_u$ is the mean length of stream segments of order u. Figure 4 is the plot of the logarithm of mean stream length against stream order. Table 2 shows the lengths of all streams in subbasins of the Frances River watershed. Results indicate that the stream lengths follow Horton's law of stream lengths (Fig 4).

Length ratio (RL) is the weighted mean length ratio and is determined by taking the antilogarithm of the slope of the best fitted regression line to a graph of the logarithm of the average stream length against stream order, according to the formula shown in Figure 4.

Main channel length (MCL) is the total length (in miles) of the main channel from the mouth of the drainage basin to the highest point in the basin running parallel to the line of dominant drainage.

Sinuosity (CSIN) is the ratio between main channel length and basin length and indicates the extent of meandering of the main stream.

Drainage area (DA) is the total area in square miles drained by the highest order of stream in that basin. Table 3 shows the areas drained by the number of streams of each order starting with third order. Scale of the available maps did not make it feasible to compute areas drained by first and second order streams. A_u is the total area of streams of order u, $\bar{A}_u$ is the average area drained by each order and is derived from A_u/N_u. Figure 5 shows the plot of the logarithm of average area drained against stream order. Subbasin areas were measured by planimeter and the procedure was repeated at least twice for accuracy. Results indicate that drainage areas follow Horton's law of stream areas (Horton, 1945).

Area ratio (RA) has a definition analogous to length ratio (RL) and is derived by taking the antilogarithm of the slope of the regression line fitted to a graph of the logarithm of average drainage area against stream order, (Strahler, 1964). As mean areas of first and second order streams are not computed, the formula is modified as shown in Figure 5.

Table 1. Frances River Basin Stream Order vs. Number of Streams

SUBBASIN	Stream order 1	2	3	4	5	6
	Number of Streams					
1	37	10	2	X		
2	113	27	6	3	X	
3	99	23	4	1	1	
4	141	36	9	X		
5	127	35	7	2	X	
6	115	31	5	1	1	
7	64	19	3	1		
8	47	11	2	1		
9	112	29	6	1	1	
10	111	29	7	1		
11	83	22	5	X		
12	105	27	7	3	1	
13	92	25	5			X
14	74	18	6	3		X
15	188	53	11	4	X	
16	38	11	3	1		
17	88	26	7	1	1	
18	73	20	6			X
19	86	19	5	2	1	
20	40	12	4	1		X
21	59	15	5	1		X
** TOTAL (10AB001)	1892	498	115	27	6	X
22	12	2				1
TOTAL	1904	500	115	27	6	1
BF RATIO	3.81	4.35	4.26	4.50	6.00	

* X denotes the stream order in which the stream leaves the Subbasin.
** gauging station 10AB001 is located above the junction of Frances and Liard rive

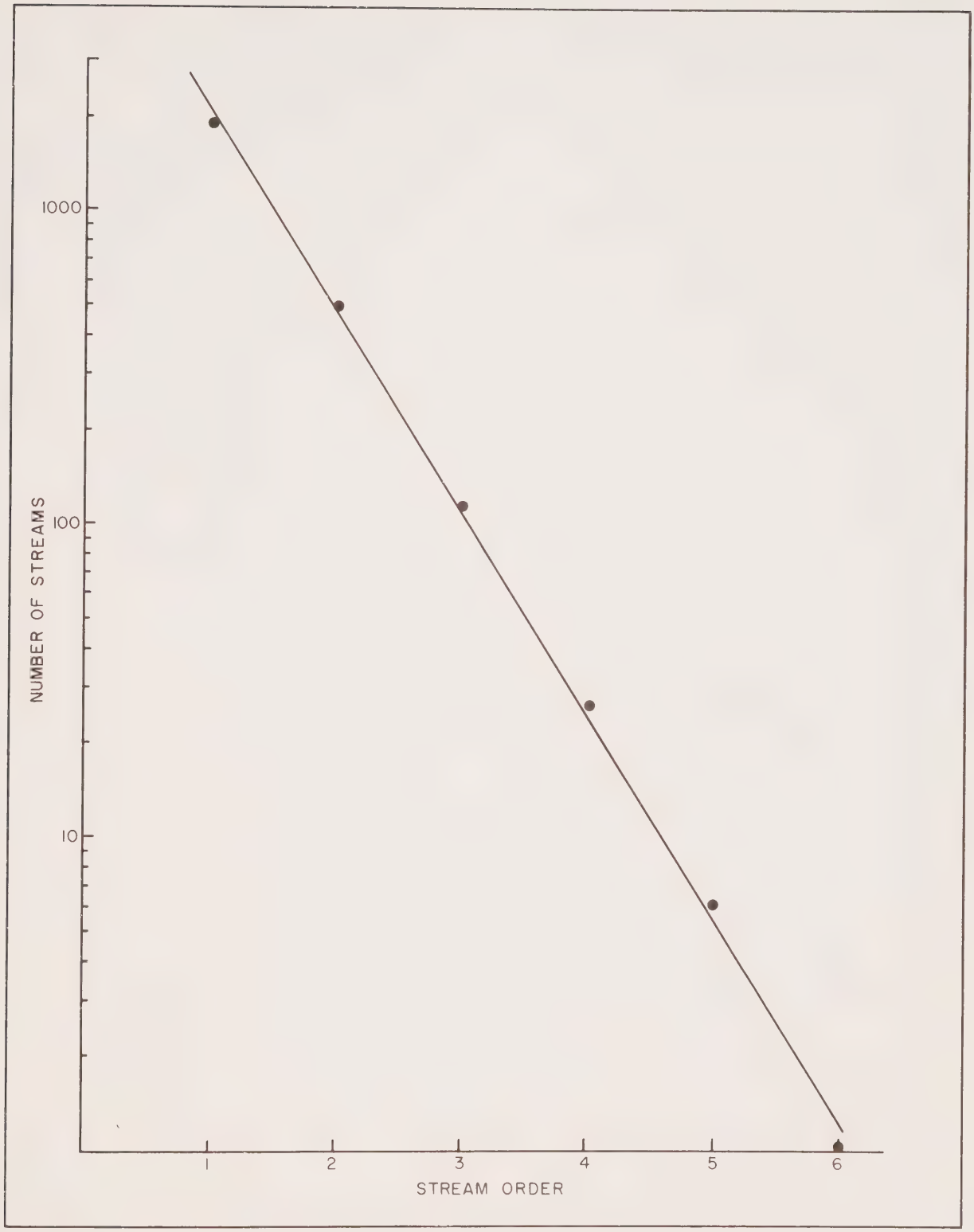


Figure 3. Frances River Basin; stream order vs. number of streams.

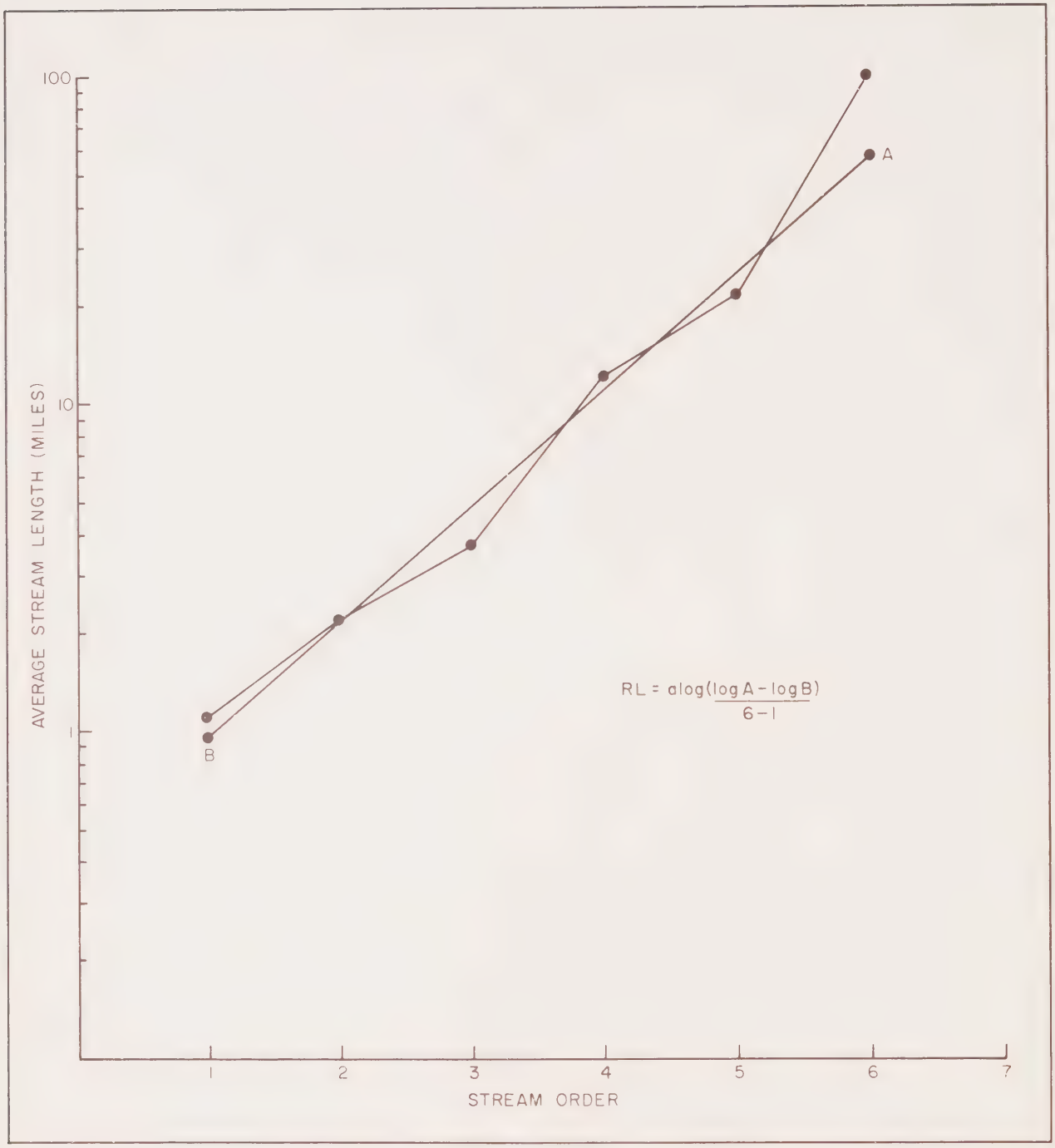


Figure 4. Frances River Basin; stream order vs. average stream length.

Table 2. Frances River Basin. Stream Length (L) of Stream Order 1 to 6 in miles.

SUBBASIN	Stream Order 1	2	3	4	5	6	Drainage density (miles miles^{-2})
			L (Miles)				
1	58	20	19	4*			0.720
2	126	71	12	32	11		0.798
3	125	49	22	12	24		0.813
4	120	73	25	22			1.225
5	115	45	24	16	8		1.070
6	120	55	19	9	24		0.945
7	44	48	12	28			0.564
8	48	35	14	11			0.771
9	155	59	33	24	3		0.872
10	94	42	21	33			0.961
11	96	58	24	14			0.857
12	127	64	27	24			0.781
13	124	69	20			27	0.568
14	104	68	14	17		21	0.783
15	204	95	37	24	20		1.117
16	47	21	9	14			0.727
17	95	88	26	21	29		0.938
18	107	55	27			17	0.880
19	95	46	26	11	10		0.974
20	54	25	9	11		9	0.818
21	63	24	14	9		11	0.828
STATION 10AB001							0.850
22	22	3				15	0.482
TOTAL LENGTH	2143	1113	434	336	129	100	0.845
AVERAGE LENGTH ($\bar{L}_u$)	1.13	2.23	3.77	12.44	21.5	100	

* Underlined values correspond to the streams denoted by X in Table 1.

Table 3. Frances River Basin. Drainage Area (A) of Stream Order 1 to 6, in Miles^2

SUBBASIN	Stream Order 1	2	3	4	5	6
			A (miles^2)			
1			120			
2			129	421		
3			116	131	750	
4			89	196		
5			102	144		
6			79	111	630	
7			83	234		
8			65	140		
9			202	311	688	
10			101	198		
11			169			
12			160	438	534	
13			116			
14	Not computed	Not computed	174	209		
15			189	237		
16			58	125		
17			177	90	741	
18			164			
19			128	158	193	
20			49	120		
21			53	67		
Station 10AB001						
22						5035
TOTAL AREA			2512	3330	3533	5035
AVERAGE AREA ($\bar{A}_u$)			22.4	123.3	589.0	5035

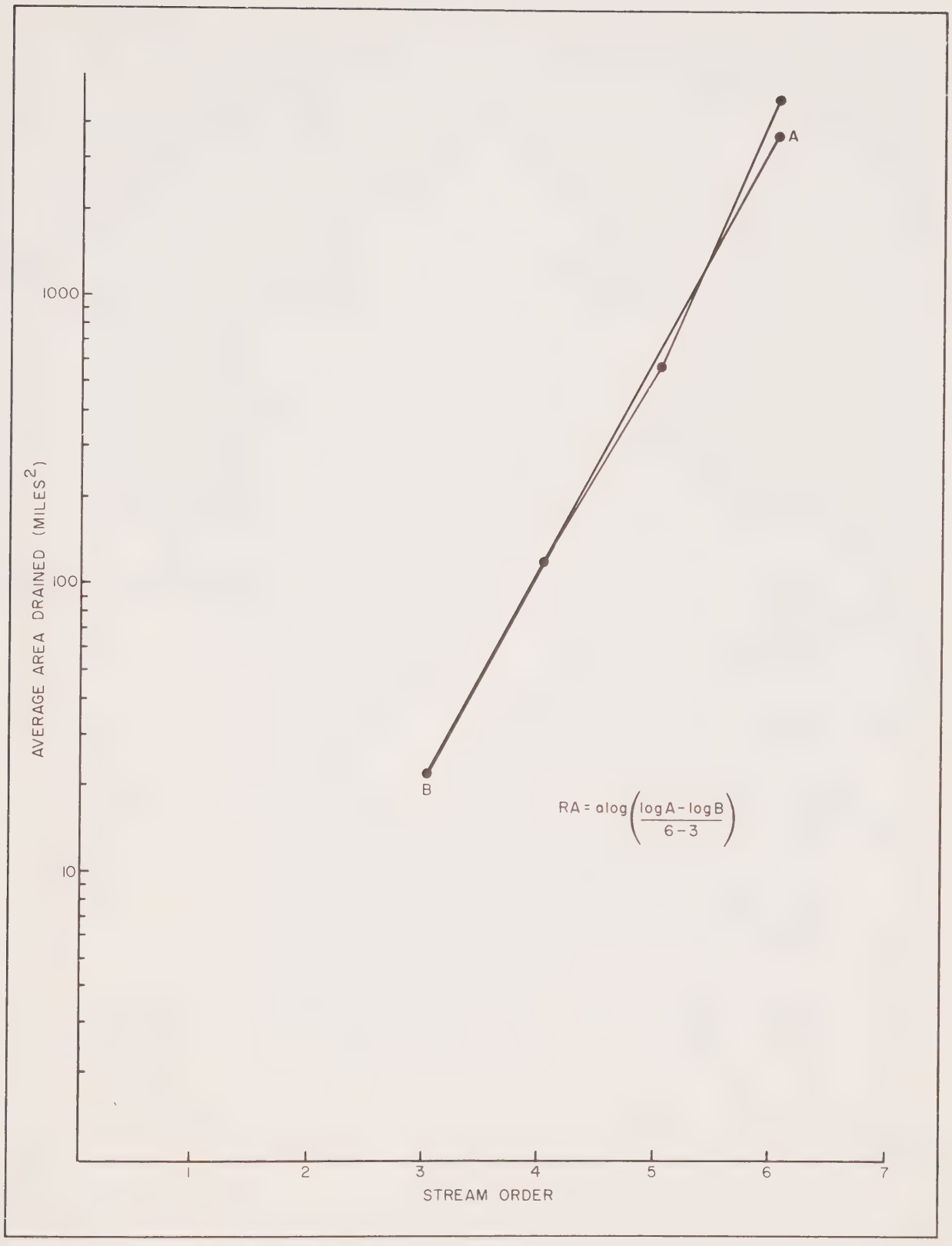


Figure 5. Frances River Basin; stream order vs. average area drained.

Drainage density (DD) is the ratio of total stream length in miles for all streams in the basin to total basin area in square miles. The results are presented in Table 2.

Channel frequency (F) is defined as the number of streams per unit area -

$$F = \frac{N_u}{A_u}$$

Constant of channel maintenance (CCM) is the smallest area of watershed, in square feet, required to sustain one foot of channel drainage.

$$CCM = \frac{5,280}{DD} \quad (1 \text{ mile} = 5,280 \text{ feet})$$

Basin perimeter (CP): The total basin perimeter in miles is measured by tracing the basin outline with chartometer. Table 4 gives results for cumulative perimeters of subbasins and their respective drainage areas measured progressively down stream at junctions of subbasin streams and the main channel. Figure 6 shows a plot of drainage area against perimeter of the subbasins as they are measured along the main channel from the drainage divide to the mouth of the watershed.

Circularity ratio (RC) is defined as the ratio of the area of a basin to the area of a circle with the same perimeter (Miller, 1953)

$$RC = \frac{DA}{AC}$$

where AC = constant = $\frac{(\text{Perimeter})^2}{4\P}$

Elongation ratio (RE) is defined as the ratio between the diameter, d, of a circle having the same area as the basin, and the basin length LB, (Schumm, 1956)

$$RE = \frac{d}{LB}$$

where $d = 2(DA/\P)^{1/2}$

Area - distance profile is a plot between the drainage area of sub-basins and the distance along the main channel from the drainage divide to the mouth of stream (Fig 7). Table 4 gives the results for the Frances River Basin.

Altitude - length profile of the watershed is shown in Figure 8. The data necessary for this plot were derived from the map by measuring the distance along the main channel as it intersected successive contours. Table 5 shows the results of this analysis.

The hypsometry (area-altitude) of each basin was measured by random dot overlay, the cumulative percentage of dots calculated, and a hypsometric

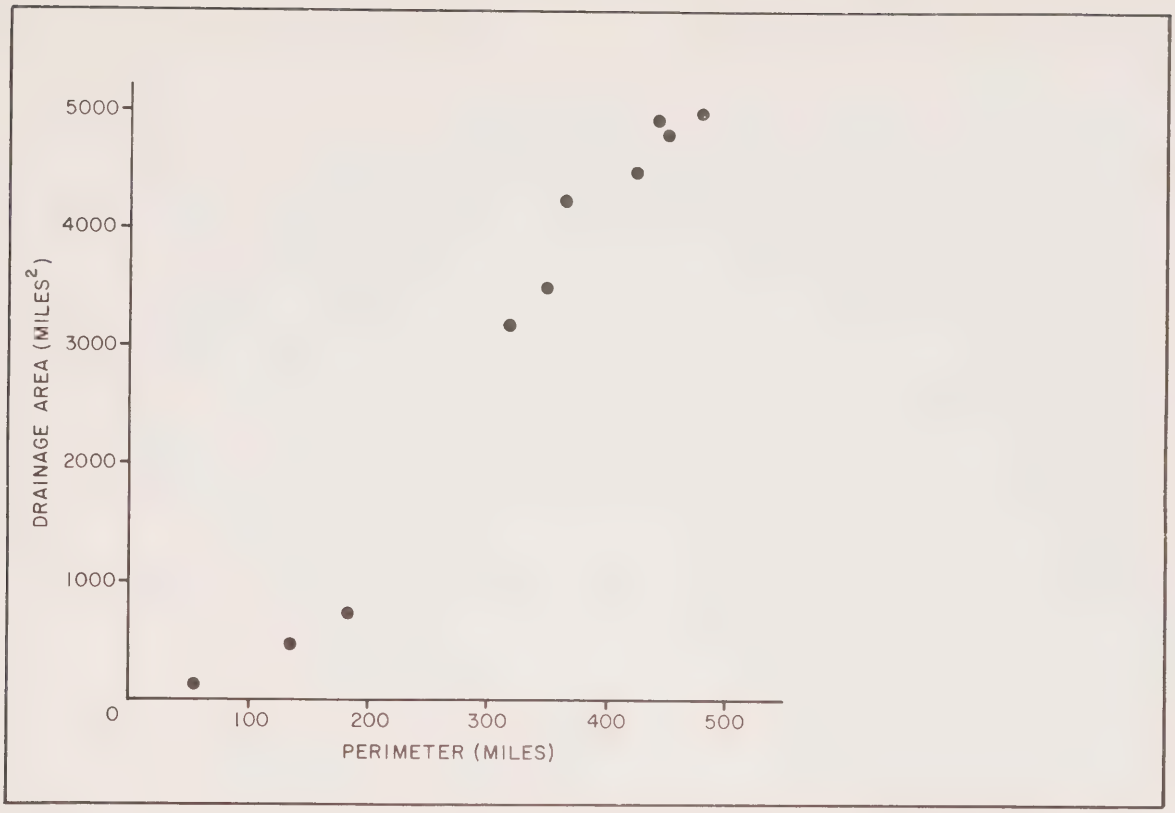


Figure 6. Frances River Basin; perimeter vs. drainage area.

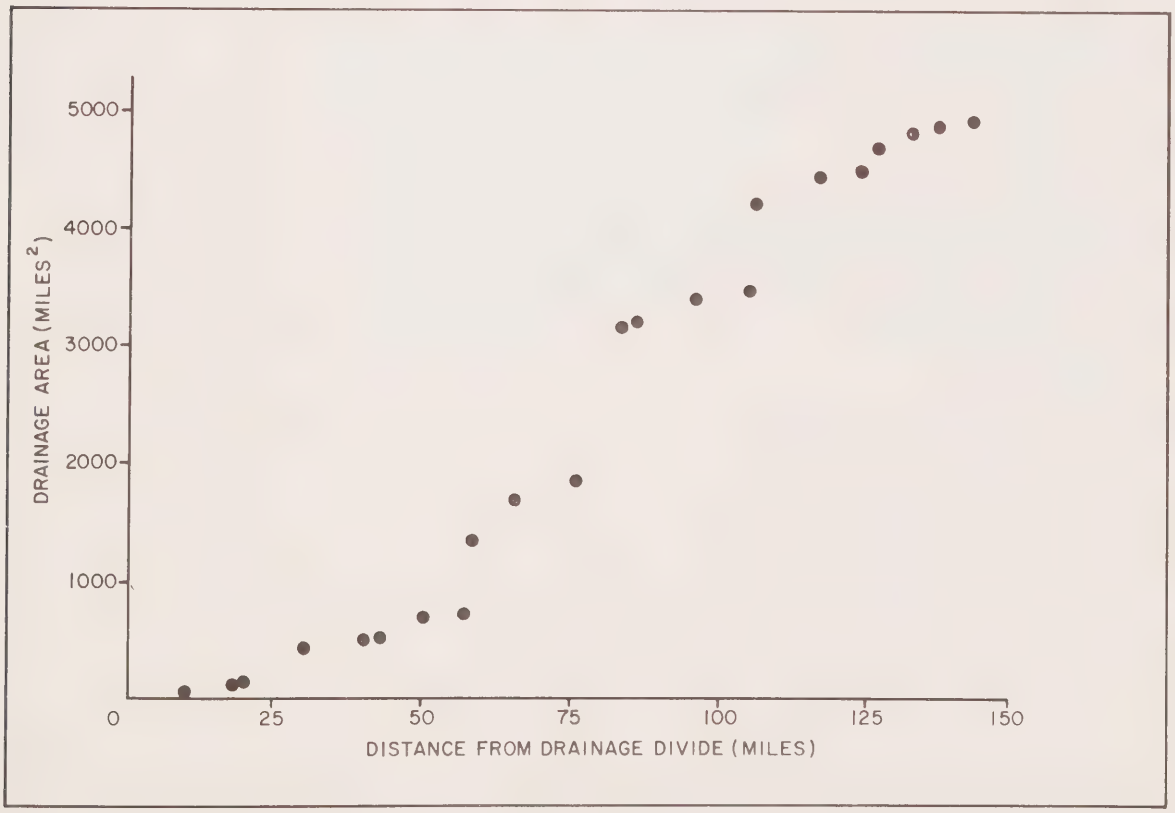


Figure 7. Frances River Basin; distance from drainage divide vs. drainage area.

Table 4. Frances River Basin. Morphometry of Subbasins.

Subbasin	Area (Miles^2)	Main Basin* Perimeter (Miles)	Lengths (Miles)* MCL	LB	Area (Miles^2) Covered By: Lake	Forest	Swamp	Glacier
1	139	54	18	16	-	47	-	-
2	316	137	33	29	11.1	176	-	8.0
3	285	185	57	50	10.3	245	-	5.0
4	196				12.5	140	-	-
5	194				9.2	68	-	3.0
6	240				5.8	189	-	1.6
7	234				7.6	168	-	4.2
8	140				4.1	94	1.1	1.8
9	314				6.1	139	4.5	3.1
10	198				-	121	-	8.2
11	224				-	81	-	-
12	310				1.1	216	-	1.5
13	422	318	83	69	44.0	350	-	6.7
14	286	351	104	87	15.8	231	-	3.0
15	348				5.5	215	-	17.0
16	125				3.6	94	-	1.9
17	276				9.1	271	-	7.4
18	234	426	122	104	0.9	190	-	4.1
19	193				2.5	186	-	2.3
20	132	453	129	110	12.0	107	-	10.0
21	146	443	140	119	0.5	131	-	10.0
STA. 10AB001								
22	83	480	155	133	0.3	82	-	9.1
TOTAL AREA	5035							
			TOTAL AREA (MILES^2) COVERED		162.0	3541	6.6	107.9
			PERCENT AREA COVERED		3.22	70.4	0.13	2.14

* Lengths and Perimeter measured progressively downstream at junctions where subbasins drain directly into the main channel.

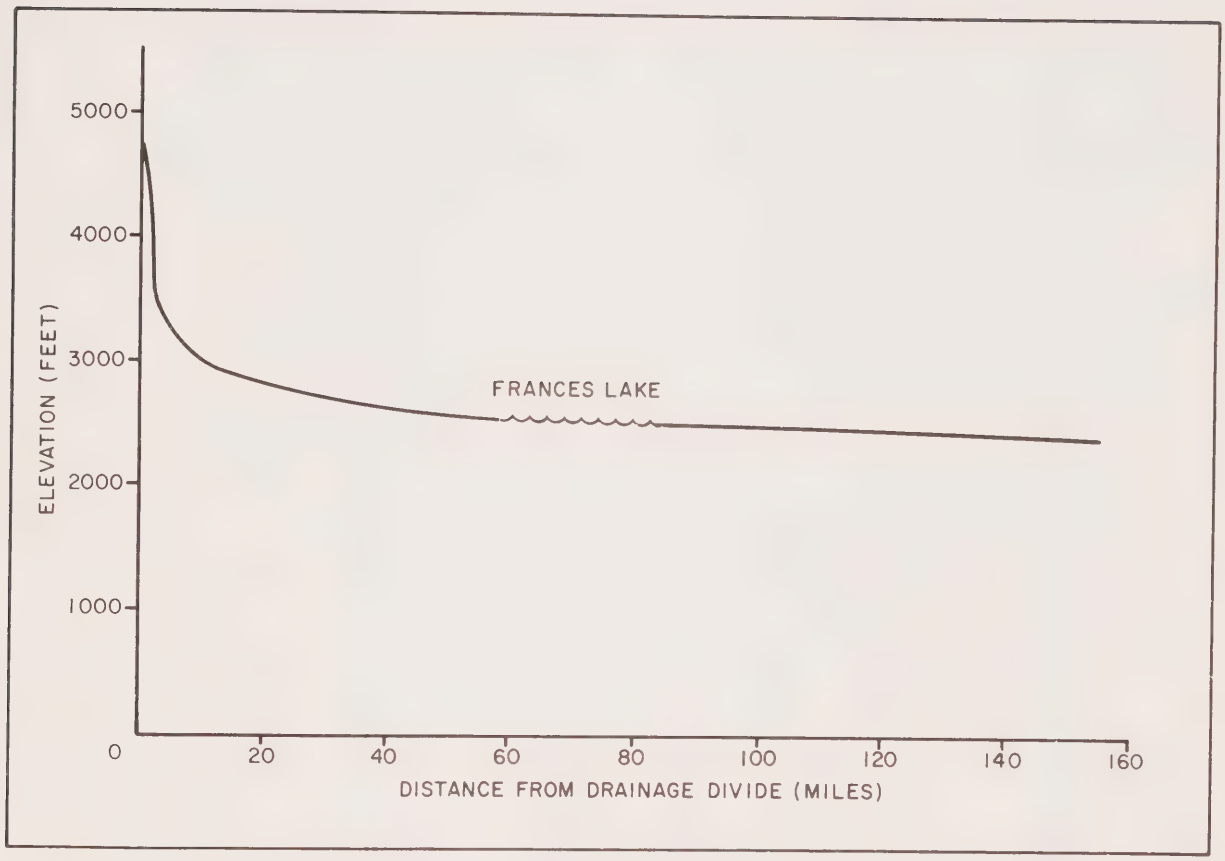


Figure 8. Frances River Basin; altitude-length profile.

Table 5. Frances River Basin. Longitudinal Profile of Main Channel

Main Channel Distance To Drainage Divide (Miles)	Main Channel Distance From Drainage Divide (Miles)	Cumulative Area ($Miles^2$)	% Area	Elevation Ft	Slope Ft/Miles
0	155	0	0.00		
1				4500	500.0
1.5				4000	1000.0
2				3500	1000.0
10	145	57	1.30	3000	62.5
18		139	2.76		
20	135	159	3.16		
30	125	445	8.84		
33		455	9.04		10.40
40	115	500	9.95		
50	105	708	14.05		
57		740	14.70		
58		1370	27.20	2540	
65	90	1708	33.90	FRANCES	
75	80	1828	36.30	LAKE	
83		3212	64.20	2540	
85	70	3229	64.60		2.10
95	60	3432	68.20		
102				2500	
104		3498	69.60		
105	50	4247	85.00		
115	40	4430	88.00		
122		4481	89.00		
125	30	4671	92.80		9.82
131		4806	95.50		
135	20	4894	97.30		
141	14	4952	98.40		
145	10	4970	98.90		
155	0	5035	100.00	2400	

curve drawn. Table 6 and Figure 9 give the results for Frances River Basin.

Maximum (MAE) and minimum (MIE) altitude of a watershed were obtained directly from the map.

Slope factor (SLOP) in feet/mile, defines the slope of the main channel located between the points 85% and 10% of the distance d measured upstream from its basin outlet to the maximum altitude, h, of the drainage divide.

$$SLOP = \frac{h85\% - h10\%}{d85\% - d10\%}$$

The value of SLOP can be obtained from the altitude - length profile Figure 8.

Surface cover is the percentage areal distribution of lake and swamp (PLSW), forest (PF), and glacier (PGL) in each basin. The areal distribution of these features was measured directly by random dot overlay. Table 4 gives the measured values of the surface cover in Frances River Basin.

Basin relief (H, in feet) is the difference in elevation between the mouth of the basin (MIE) and the maximum altitude of the drainage divide (MAE).

Relief ratio is expressed as the ratio between the relief of a basin, H, and the longest dimension of the basin, LB, parallel to the amin drainage line:

$$RH = \frac{H}{LB}$$

Average elevation (AVE) is determined by halving the sum of maximum elevation (MAE) and minimum elevation (MIE).

Mean elevation (MEE) is that contour level which has 50% of the watershed area above it on the hypsometric curve.

Hypsometric integral (HYI) is derived by measuring the area below the hypsometric curve and expressing it as a percentage of the area below and above the curve (Gladwell, 1970), as illustrated in Figure 9.

Hypsometric coefficient (HCK) is derived by dividing the area under the curve into three sections. A vertical line is extended from the 50% point to the hypsometric curve. A horizontal line is then extended to the percent elevation axis. The area of each of the three sections, A, B, C (Figure 9) is determined and HCK found from:

$$HCK = \frac{A - C}{B}, \quad \text{(Gladwell, 1970).}$$

HCK attempts to quantify the distribution of elevation around the point of mean elevation (Fig 9).

Table 6. Frances River Basin. Hypsometric Analysis

Subbasin	Altitude Interval, Ft x 10^2									
	70-65	65-60	60-55	55-50	50-45	45-40	40-35	35-30	30-25	25-2
1	4	4	10	14	13	7	6	5	5	
2		3	9	22	16	21	44	20	16	
3			2	6	13	13	27	37	34	
4		1	2	11	14	17	25	21		
5		1	1	6	10	16	27	30		
6			2	11	17	32	24	12	4	
7	6	7	8	14	12	7	17	29	2	
8	1	5	10	7	3	8	10	16		
9	2	15	23	16	23	14	14	28	2	
10		4	6	10	15	21	19	3	2	
11	2	6	13	28	21	15	10	13		
12		4	14	27	22	20	19	21	20	
13		1	7	8	7	15	21	46	85	
14	2	2	5	13	9	10	11	36	72	1
15			7	9	15	15	23	3		
16		3	15	32	33	38	45	11		
17		1	6	13	12	26	22	29	36	2
18		3	4	14	18	11	13	27	36	9
19				2	5	14	20	22	29	6
20				1	1	3	6	13	29	20
21				2	8	8	14	12	28	8
Hydrometric Stat. 10AB001										
22							1	2	25	16
#	17	60	144	266	287	331	418	436	425	62
%	0.7	2.3	6.0	10.9	11.7	13.6	17.2	17.7	17.5	2.4
#	17	77	221	487	774	1105	1523	1959	2384	2446
Σ %	0.7	3.0	9.0	19.9	31.6	45.2	62.4	80.1	97.6	100.0
% of Height	100	89	78	67	56	44	33	22	11	0

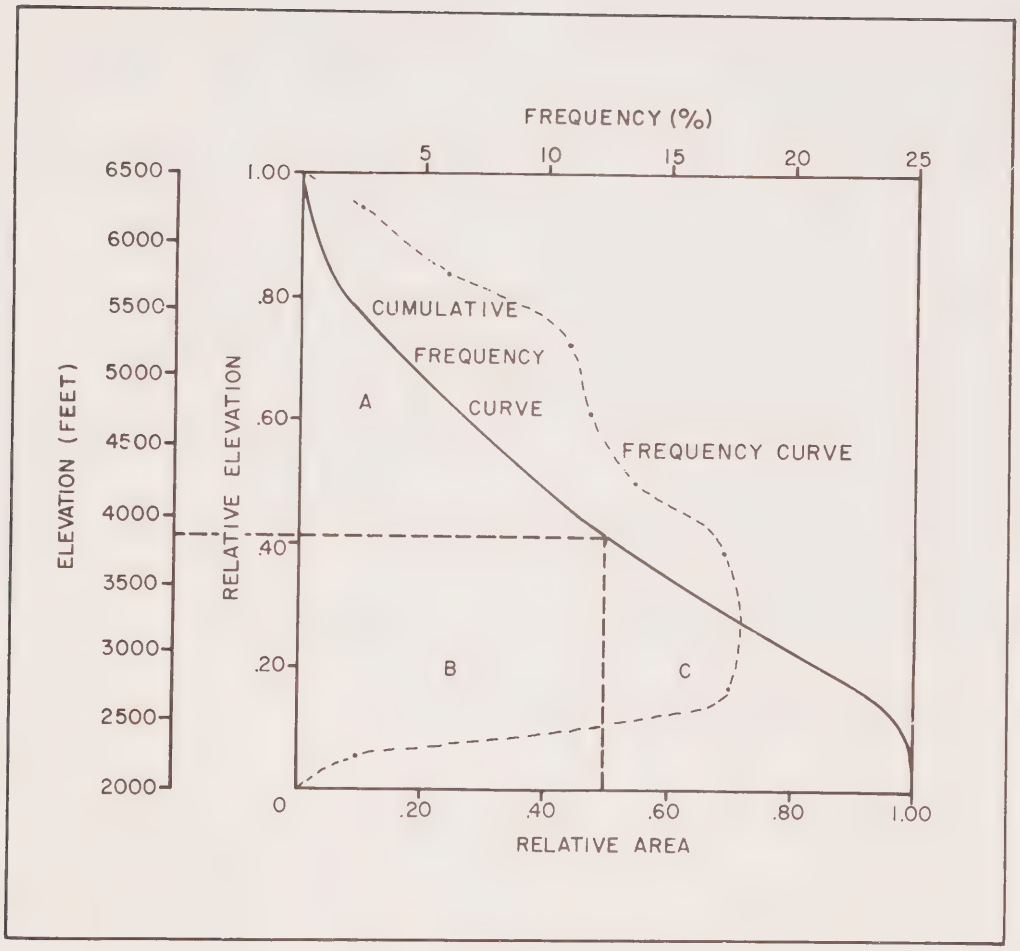


Figure 9. Frances River Basin; hypsometric curve.

Percent area above average elevation (PAA) is determined by finding the percent area corresponding to the 50% elevation mark on the hypsometric curve. The values of the following parameters are obtained from the hypsometric curve:

Percent area at elevation 0-2000 feet (PAE1)

Percent area at elevation 2000-4000 feet (PAE2)

Percent area at elevation 4000-6000 feet (PAE3)

Percent area at elevation 6000 - maximum feet (PAE4)

Mathematical calculations.

Data obtained from the morphometric analysis of Frances River Basin are used to determine the following basin parameters:

1 Circularity ratio = $\frac{\text{circumference of circle of same area as basin}}{\text{basin perimeter}} = 0.523$

2 Elongation ratio = $\frac{\text{diameter of circle of same area as basin}}{\text{LB}} = 0.601$

3 Relief ratio = $\frac{\text{total basin relief}}{\text{LB} \times 5280} = 0.0064$

4 Bifurcation ratio (weighted mean)

Order	Number	BF	No. In BF	BF x No. In BF
1	1,904	3.81	2,404	9,160
2	500	4.35	615	2,675
3	115	4.26	142	605
4	27	4.50	33	148
5	6	6.00	7	42
6	1			
			3,201	12,630

$$RB = \frac{12,630}{3,201} = 3.95$$

5 Length ratio = antilogarithm of slope of regression line fitted to plot of logarithm of stream length against stream order = 2.22

6 Area Ratio = antilogarithm of slope of regression line fitted to plot of logarithm of average area drained against stream order = 5.60

7 $\text{Drainage density} = \frac{\text{total length of streams}}{\text{total area of basin}} = 0.845$

8 $\text{Stream frequency} = \frac{\text{total number of streams}}{\text{total area of basin}} = 0.513$

9 $\text{Slope factor} = \frac{h\ 85\% - h\ 10\%}{d\ 85\% - d\ 10\%} = 3.01$ ft/mile

where h = elevation at 85% and 10% from mouth of river, and

d = distance from mouth of river (Figure 8)

10 $\text{Channel maintenance constant} = \frac{5280}{\text{drainage density}} = 6{,}250\ \text{ft}^2$

11 $\text{Average elevation} = \frac{\text{max. el.} + \text{min. el.}}{2} = 4{,}550$ ft

12 Mean elevation (from hypsometric curve) = elevation at 50% area = 3,850 ft (Figure 9)

13 Hypsometric integral = percentage of area below the hypsometric curve = 43.3% (Figure 9).

14 $\text{Hypsometric coefficient} = \left(\frac{A-C}{B}\right) = -0.05$ (Figure 9)

15 PAE1 = 0.0

16 PAE2 = 55.0

17 PAE3 = 43.0

18 PAE4 = 2.0

Hydrologic characteristics

Magnitude and frequency of floods.

The frequency of floods is expressed in terms of recurrence interval. A flood with a recurrence interval of 10 years has a 10% chance of being equalled or exceeded in any one year; however, because of the erratic nature of flood events, a flood with a recurrence interval of 50 years may not occur in a 50-year period or may occur several times in 50 years. In general, it can be said that 50-year floods may occur approximately 20 times in a period of 1000 years.

The flow characteristics selected for the current study are as follows:

1) Mean annual flow (MAF),

2) Mean annual flood (T),

3) Mean annual 50-year flood (MAFF), and

4) Mean annual 100-year flood (MAFH).

The annual values were selected because they are sufficiently accurate for many of the approximations required in the analysis. The values are expressed in cubic feet per second per square mile of drainage area.

Definitions of hydrologic characteristics, after Langbein and Iseri, (1960) are:

Flood is any relatively high streamflow as measured by gauge height or discharge quantity. For the present analysis base floods were computed for each gauging station according to the methods suggested by Dalrymple (1960).

Recurrence interval is the average interval of time within which a given flood will be equalled or exceeded only once.

Mean annual flow (MAF) is the average flow of all complete water years used in this study.

Mean annual flood (T) is that flood which has a recurrence interval of 2.33 years. In other words, once in every 2.33 years on the average the highest flow of the year will exceed the mean annual flood. (Chow, 1964, p.23). It is derived from the regression line fitted to a plot of logarithm of discharge against recurrence interval.

Mean annual flood with 50-year recurrence interval (MAFF) is the flood that will be equalled or exceeded once in fifty years and is derived from the regression line in flood frequency analysis (Figures 10-15).

Mean annual flood with 100-year recurrence interval (MAFH) is the flood that will be equalled or exceeded once in one hundred years and is derived from the regression line in flood frequency analysis (Figures 10-15).

Hydrologic data

Records of surface runoff for the study area were searched thoroughly. There are 14 watersheds with gauged records for the periods indicated in Table 7. Unfortunately, the study area is sparsely gauged (Figure 1) and the records are relatively short. The records for gauging stations 10HB001, 10M001 and 10MB001 are also irregular. Stations 10BB002 and 10BA001 gauge 4249 and 2419 square miles, respectively, of the Kechika River Basin (10BB001). Station 10AB001 gauges 4952 square miles of the Liard River Basin (10AA001). All other gauges represent independent watersheds. Hydrologic records of greatest possible length were desired since the characteristics computed from such records can be expected to include a smaller time-sampling error.

Eleven gauged watersheds were used for analytical purposes and range in size from 682 to 13,675 miles^2. The shortest record length used was 4 years and the longest, 22 years, (Table 7).

Table 7. Hydrologic Data Available For the Subbasins of the Mackenzie River.

Station Number	Subbasin	Period of Discharge Records
10AA001	Liard	1960-70
10AB001	Frances	1963-70
10AC002	Dease	1958-70
10AC004	Blue	1963-70
10AD001	Hyland	1949-70
10BA001	Turnagain	1967-70
10BB001	Kechika	1963-70
10BB002	Kechika	1967-70
10BC001	Coal	1961-70
10EA003	Flat	1960-70
10EB001	South Nahanni	1961-70
10HB001	Redstone	1964-70
10MA001	Peel	1962-70
10MB001	Snake	1963-70

Hydrologic data analysis

The selected hydrologic characteristics were estimated from the available hydrologic data. Records of three gauging stations, 10HB001, 10MA001 and 10MB001, permitted estimation of mean annual flow only, which was computed by averaging the total flow rates of all the complete water years. The standard flood frequency analysis was performed on the series of maximum instantaneous flow rates for 11 other gauged watersheds, selected according to criteria outlined by Dalrymple (1960) Plots of observed peaks and the straight line fitted by the flood frequency analysis for these watersheds are shown in Appendix 1 (Figures 10-15).

Multiple regression analysis

Multiple regression analysis was used to develop the relationships between estimated hydrologic characteristics (dependent variables) and morphometric characteristics for the gauged basins (independent variables). Despite the inability of these relationships to describe the fundamental causes of streamflow variation, the basin characteristics significant in the relationships are considered as numerical measures that are related to the flow variations. The accuracy of the defined relationship is measured by standard error of the estimate and indicates the streamflow variation unexplained by the basin characteristics (Thomas and Benson, 1970). A 5% level of significance for each independent variable and 0.8 as the minimum value of correlation coefficient (when significant independent variables are included) are taken as requirements of good statistical fit.

One of the practical prerequisites in multiregression analysis is that the independent variables should not be interrelated. To investigate tha amount of non-independence, a simple correlation matrix of the evaluated basin characteristics was obtained. In a matrix, a value of 1.00 indicates perfect correlation, 0 indicates complete independence and -1.00 indicates perfect inverse correlation. From the matrix, the highly intercorrelated variables were replaced by only one variable in the multiple-regression analysis.

It became quite evident from the results of numerous analyses that not more than three independent morphometric characteristics could be used to estimate hydrologic characteristics successfully. Attempts were made to include more variables but the resulting equations proved to be too sensitive to regional inconsistencies and used up too many degrees of freedom. The major problem in this kind of analysis is one of sample size. One part of the region may have statistical characteristics significantly different from the characteristics of another. These shortcomings are recognized and attempts are being made to improve mathematical techniques and procedures applicable to the available data.

Each regression equation developed appears to fulfill the normal requirement of a good statistical fit, i.e. each independent variable being significant at 5% level and the value of correlation coefficient being greater than 0.8 (Table 8). Equations 1-4 estimate the selected hydrologic characteristics of the gauged basins.

(1) Mean Annual Flow (MAF)=0.00007(DA)+0.00026(MEE)-0.9391(RL)+2.038

(2) Mean Annual Flood (T)=-7.504(HCK)-2.576(RL)-0.118(SLOP)+10.57

Table 8. Multiple-Regression Analysis - Significant Morphometric Variables presented in order of entry into the multiple regression equations.

VARIABLES ESTIMATING MEAN ANNUAL RUNOFF

	MEE	RL	DA
Correlation Coefficient R	0.7141	0.8570	0.9161
Coefficient of Determination R^2	0.5100	0.7345	0.8393
Stepwise Increase in R^2	0.5100	0.2245	0.1048
Level of Significance	5%	1%	1%
Standard Error of Estimate	0.2359	0.1857	0.1560

VARIABLES ESTIMATING MEAN ANNUAL FLOOD

	RL	HCK	SLOP
Correlation Coefficient R	0.6946	0.7490	0.8262
Coefficient of Determination R^2	0.4825	0.5610	0.6826
Stepwise Increase in R^2	0.4825	0.0785	0.1217
Level of Significance	5%	5%	5%
Standard Error of Estimate	0.9666	0.9518	0.8741

VARIABLES ESTIMATING MEAN 50-YEAR FLOOD

	RL	DD	CLO
Correlation Coefficient R	0.5680	0.7767	0.8336
Coefficient of Determination R^2	0.3227	0.6032	0.6949
Stepwise Increase in R^2	0.3227	0.2806	0.0916
Level of Significance	5%	5%	5%
Standard Error of Estimate	2.3577	1.9139	1.7944

VARIABLES ESTIMATING MEAN 100-YEAR FLOOD

	DD	RL	CLO
Correlation Coefficient R	0.5810	0.7823	0.8368
Coefficient of Determination R^2	0.3376	0.6120	0.7002
Stepwise Increase in R^2	0.3376	0.2744	0.0881
Level of Significance	5%	5%	5%
Standard Error of Estimate	2.5686	2.0850	1.9595

(3) Mean Annual 50-Year Flood (MAFF)=0.575(CLO)+15.45(DD)-9.58(RL)-55.21

(4) Mean Annual 100-Year Flood (MAFH)=0.620(CLO)+18.23(DD)-9.90(RL)-61.80

Attempts were made to apply these equations to the ungauged basins where detailed morphometric analysis has been carried out. For watersheds with drainage areas more than 10,000 miles^2, equation (1) tended to over-estimate mean annual discharge. An alternative equation (5) was developed in which the next important morphometric parameter was included after preventing drainage area from entering into the relationship. Similarly, an alternative equation (6) was developed for estimating mean annual flood for the basins with a value of hypsometric integral greater than +0.5. Mean 50-year and 100-year floods were estimated by equations (7) and (8) for basins with longitude greater than 137.0 or less than 123.0.

(5) Mean Annual Flow (MAF) = 0.00048(MEE)-1.368(RL)-0.054(HYI)+4.78

(6) Mean Annual Flood (T) = 0.738(CLO)- 0.0028(MIE)-4.774(RL)-72.543

(7) Mean Annual 50-Year Flood (MAFF) = 0.00041(DA)-8.640(RL)+13.974(DD)+15.803

(8) Mean Annual 100-Year Flood (MAFH) = 0.00045(DA)-8.777(RL)+16.642(DD)+14.888

It should be pointed out that equations 5-8 do not estimate hydrologic characteristics significantly different from equations 1-4 for the ungauged basins where the latter were applied. The results of the analysis are presented in tables in Appendix 2.

RESULTS

Morphometric characteristics

Complete morphometric analysis was carried out for 54 watersheds listed in Table 9, Appendix 2. In all, 33 parameters including longitude and latitude for each watershed were measured. All the primary tributary watersheds draining directly into the Mackenzie River or Arctic Ocean are listed in Table 10. Hypsometric profiles of these primary basins are indicated in Appendix 1 (fig. 16-28). So far morphometric data have been collected for approximately 150,000 miles^2.

From the results of the analysis it can be seen that the eastern side of the Mackenzie River is characterized by a high percentage of lake and swamp area. The poor drainage conditions are indicated by lower drainage density values. The watersheds on the eastern side have smaller drainage areas, with lower mean elevations and gentle slopes. The whole study area is free of large glaciers. The preliminary hypsometric analysis seems to indicate that most of the basin profiles for tributaries on the east side of the Mackenzie are in equilibrium, whereas some adjustments have yet to take place in the basin slopes of western tributaries. The analysis of morphometric characteristics is incomplete. Attempts are being made to develop and apply refined statistical methods to the collected data.

Hydrologic characteristics

Hydrologic characteristics for 11 gauged watersheds were estimated as shown in Table 11, Appendix 2. These estimated values were used to develop regression equations (1-4), relating them to the three most significant morphometric characteristics. The hydrologic characteristics of the gauged basins were then recomputed from regression equations. The results of the estimated values (from the observed data of 11 gauged basins) and the computed values (from regression equations) are compared in Table 12, Appendix 2.

The results, expressed graphically in Figures 29-32, compare favourably. The regression equations are applied to ungauged basins and the values of hydrologic characteristics of all the watersheds in the study are presented in Table 13, Appendix 2. The values of the hydrologic characteristics of the 26 primary watersheds draining into the Mackenzie and the Arctic Ocean and likely to be crossed by pipelines are indicated in Table 10, Appendix 2.

From the results it is seen that flood values per unit area of the drainage basins on the western side seem to be higher than in the basins on the eastern side.

The results presented are introductory in nature. Attempts are being made to improve the estimates by application of more sophisticated mathematical methods.

CONCLUSIONS

1) Of 33 defined characteristics, the significant morphometric parameters of value in estimating hydrologic characteristics related to peak flows are geographic location, drainage density, mean elevation, drainage area, slope, length ratio and hypsometric profile of the watershed.

2) Regional inconsistencies and limited sample size do not permit the estimation of peak flow characteristics with more than three significant morphometric parameters using multiple regression procedures.

3) On an equivalent unit area basis, the flood magnitudes of the east side Mackenzie River tributaries appear to be lower than those on the west side of the Mackenzie.

4) Drainage density appears to be much lower for basins on the east side of the Mackenzie than basins on the west side of the river. This results in poor drainage conditions.

5) Mean elevation of all east-side basins analysed to date does not exceed 1,000 ft, which suggests a lower flood hazard potential than in tributary basins on the western side of the Mackenzie River, where the average mean elevation exceeds 2,500 ft.

6) The proposed pipeline routes are free of any large scale glacier formation.

7) Comparison of hypsometric or area-altitude curves, which are an expression of the stage of development of watersheds indicate that basin profiles on the east side of the Mackenzie River are more mature than those on the west side. This may result in constant adjustment of slopes and consequent erosion in western watersheds.

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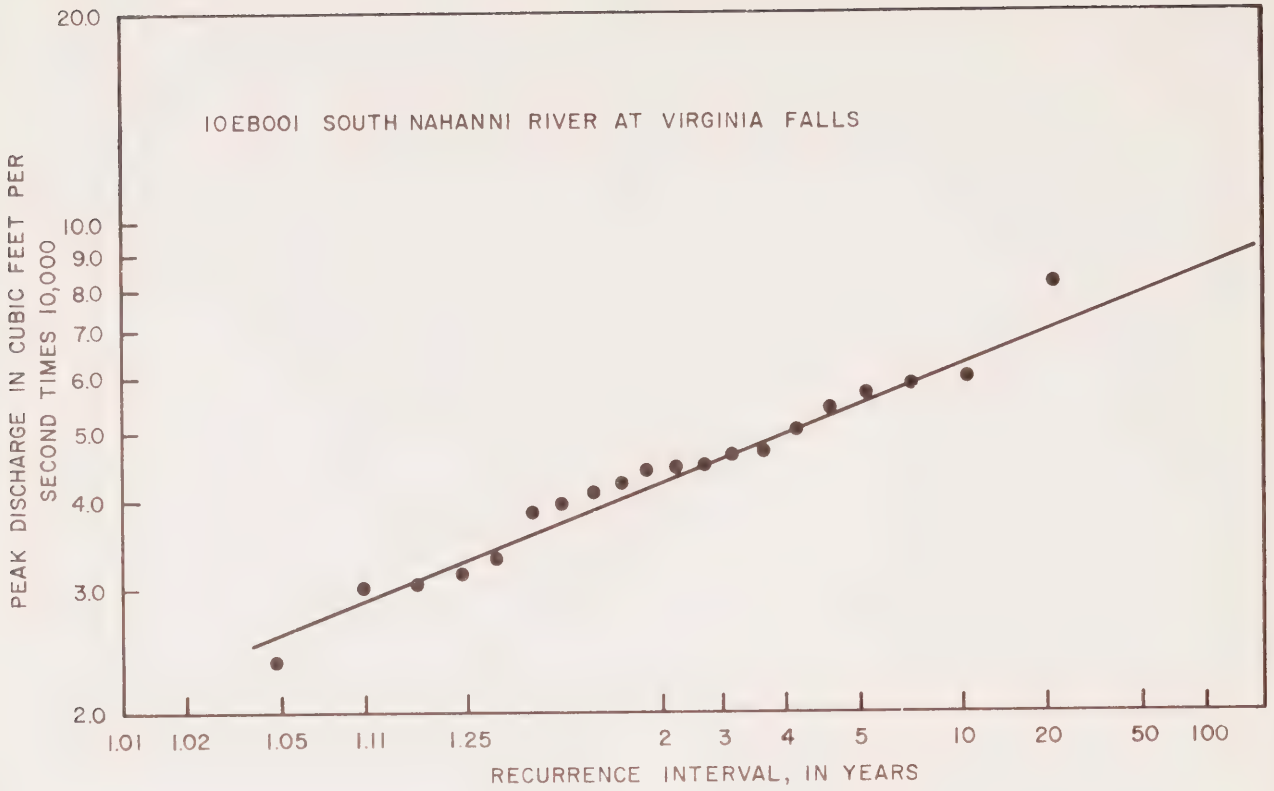
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APPENDIX I

Figures 10-15	Flood frequency analysis
Figures 16-28	Hypsometric curves
Figure 29	Mean annual flow - estimated vs. computed
Figure 30	Mean annual flood - estimated vs. computed
Figure 31	Mean annual 50-year flood - estimated vs. computed
Figure 32	Mean annual 100-year flood - estimated vs. computed.



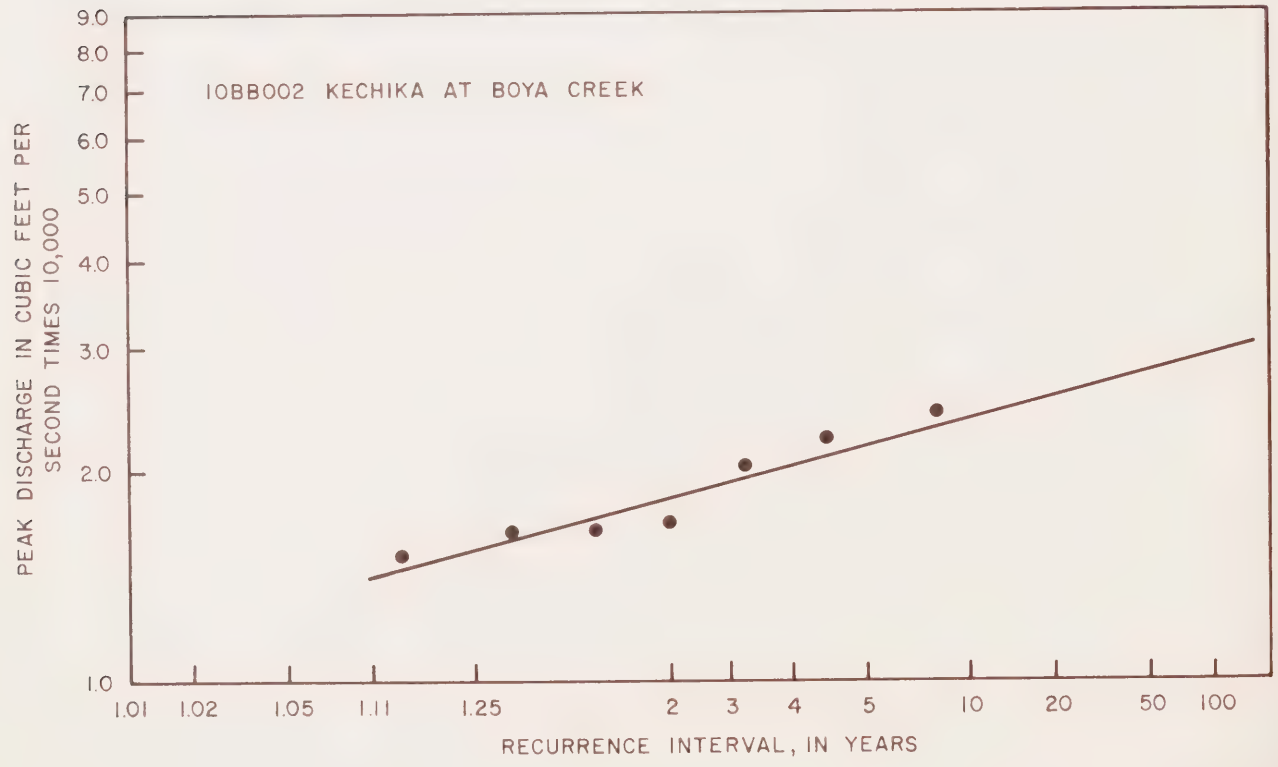
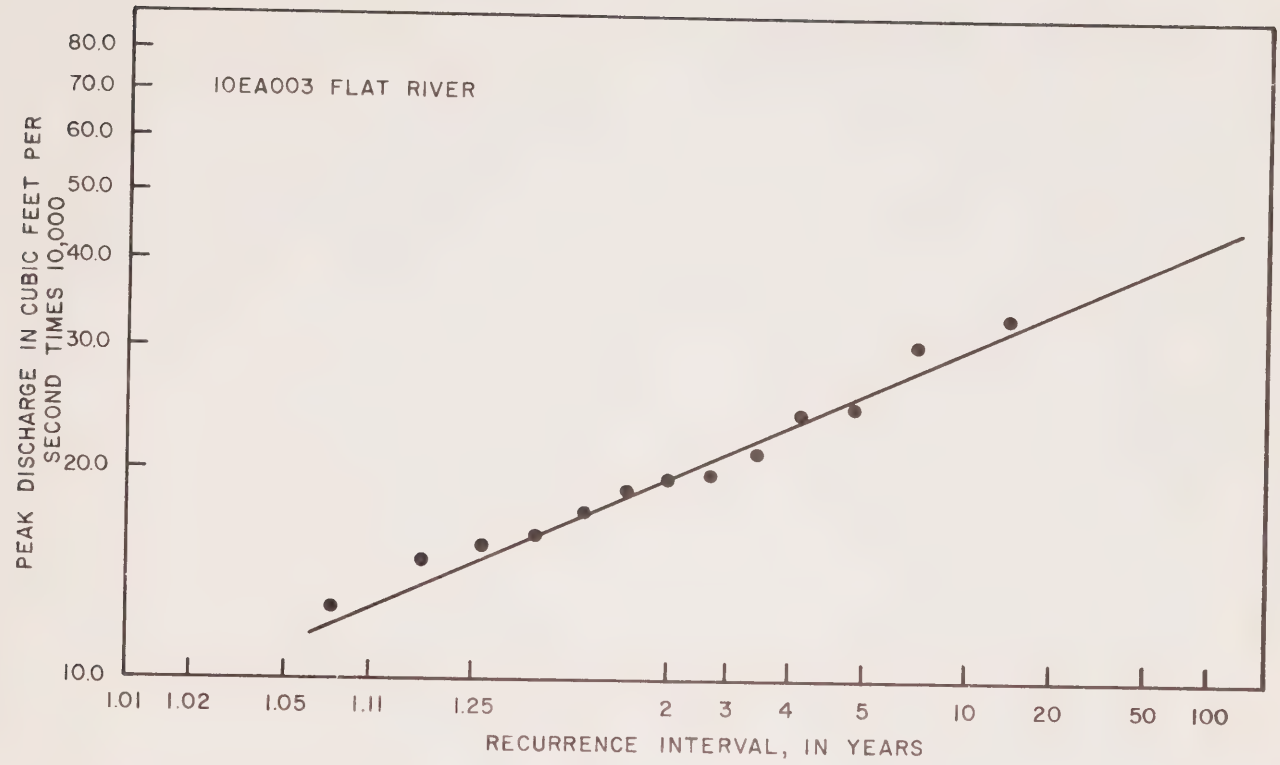


Figure 10. Flood frequency analysis.



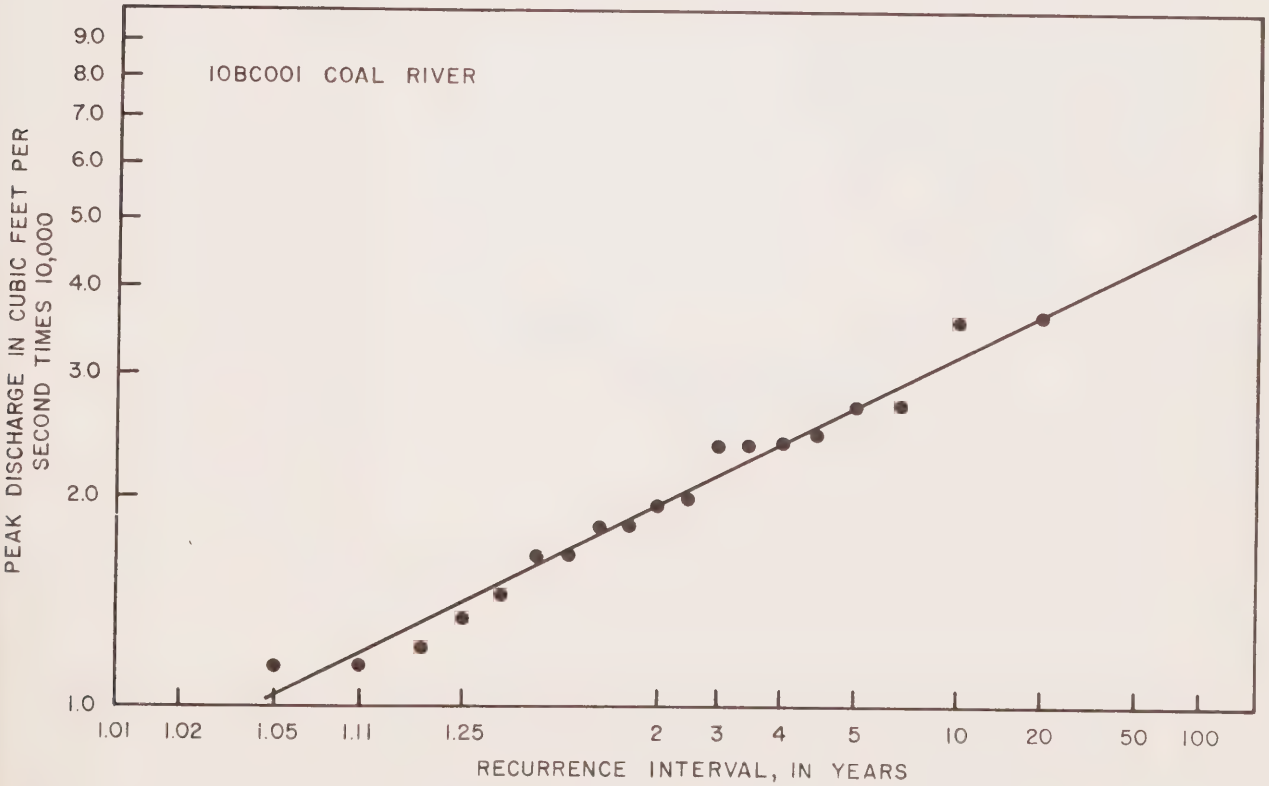
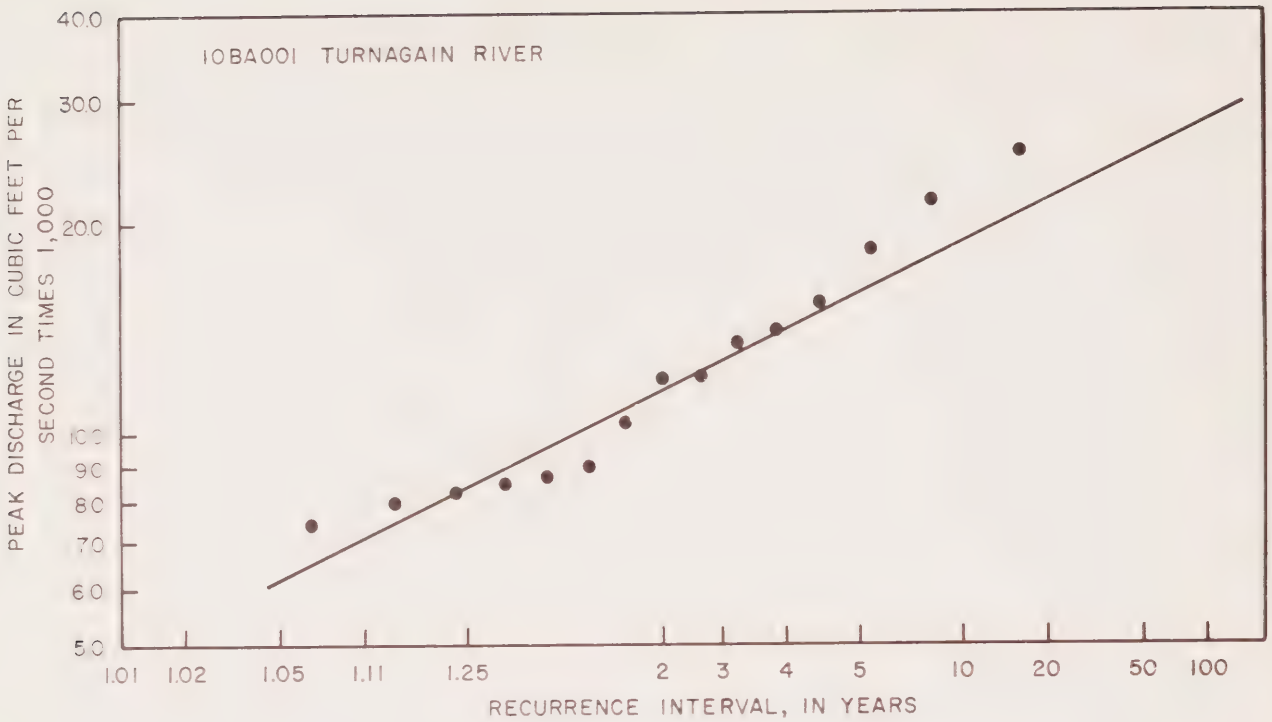


Figure 11. Flood frequency analysis.



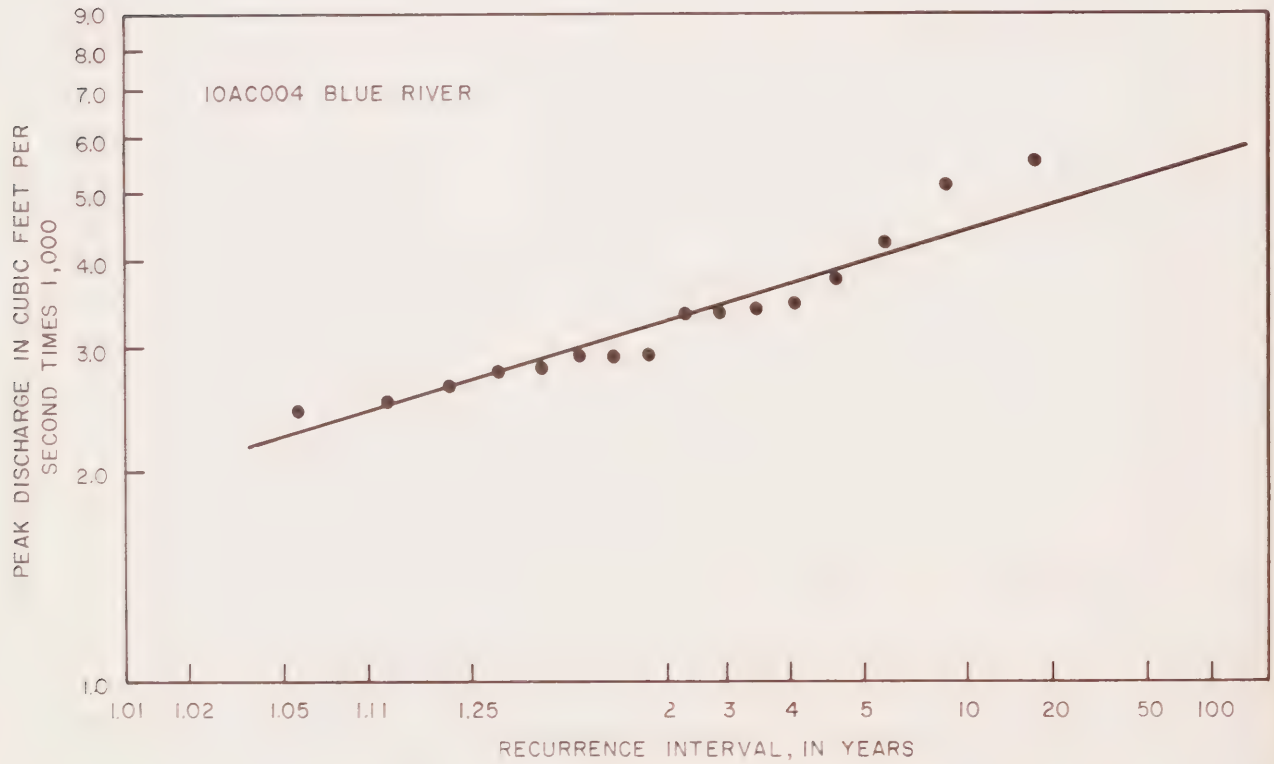
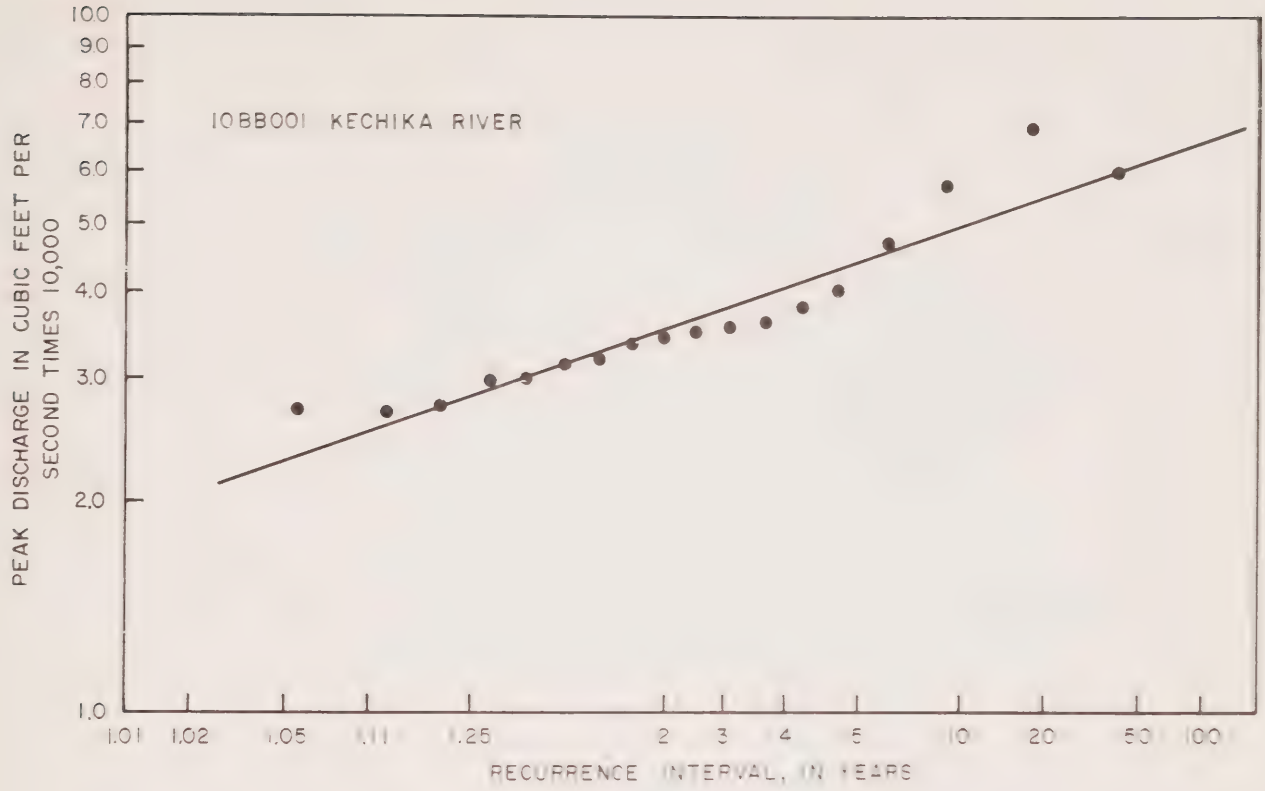


Figure 12. Flood frequency analysis.



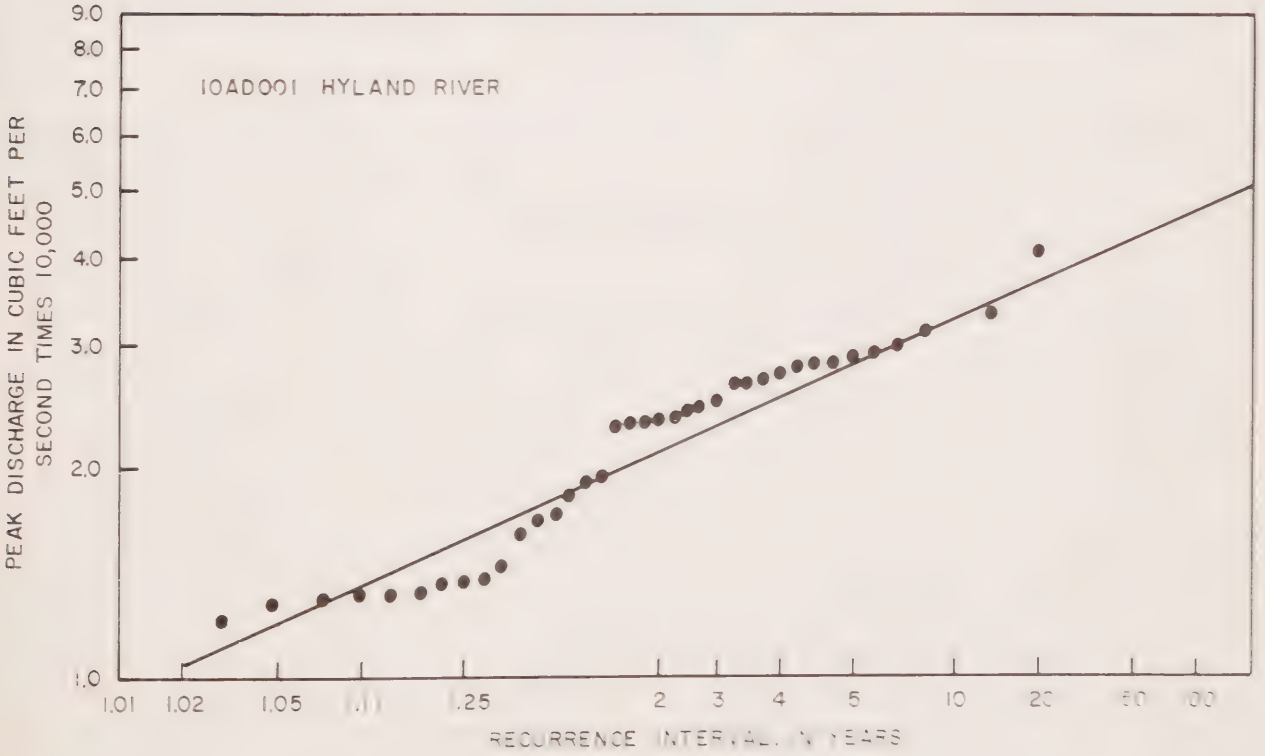
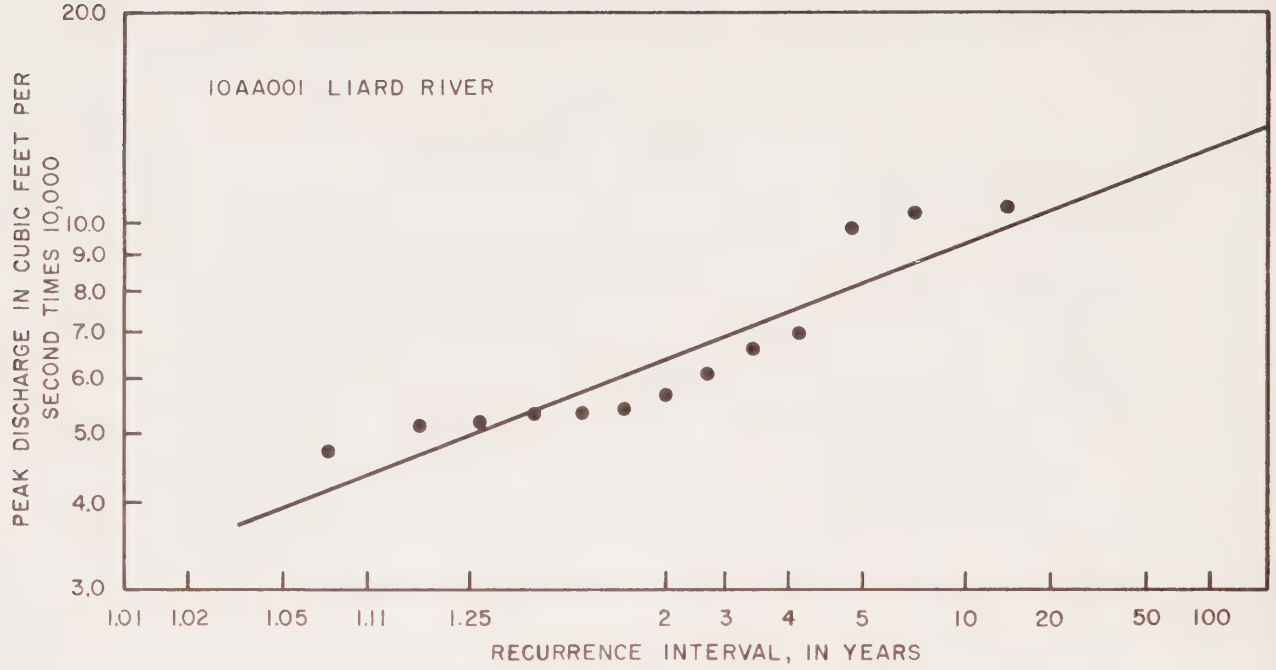


Figure 13. Flood frequency analysis.



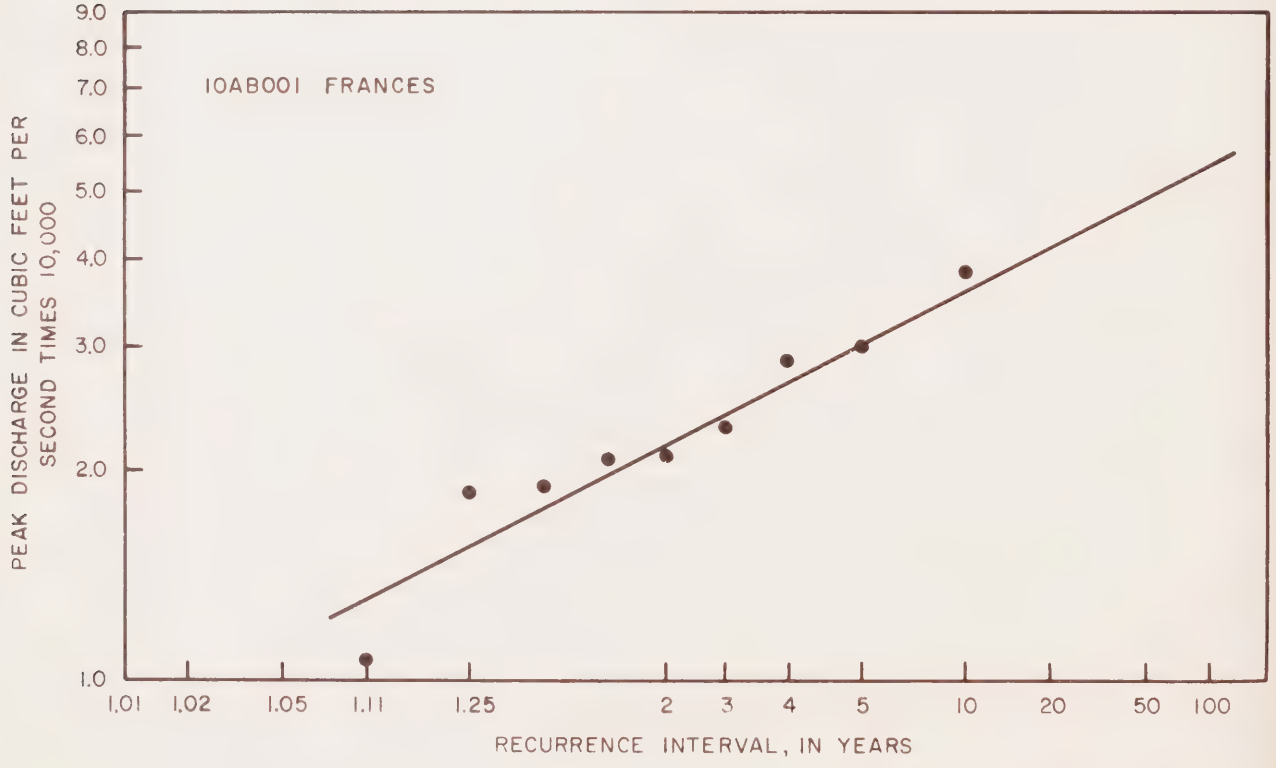


Figure 14. Flood frequency analysis.

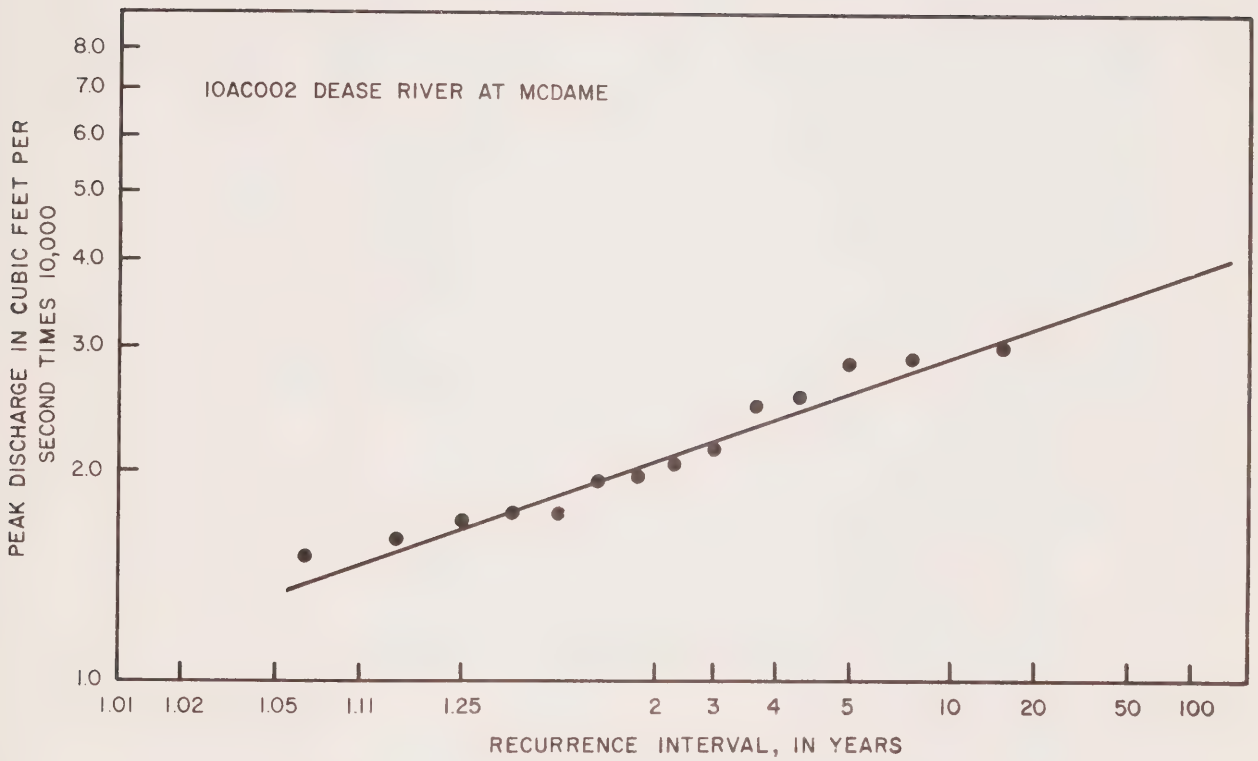


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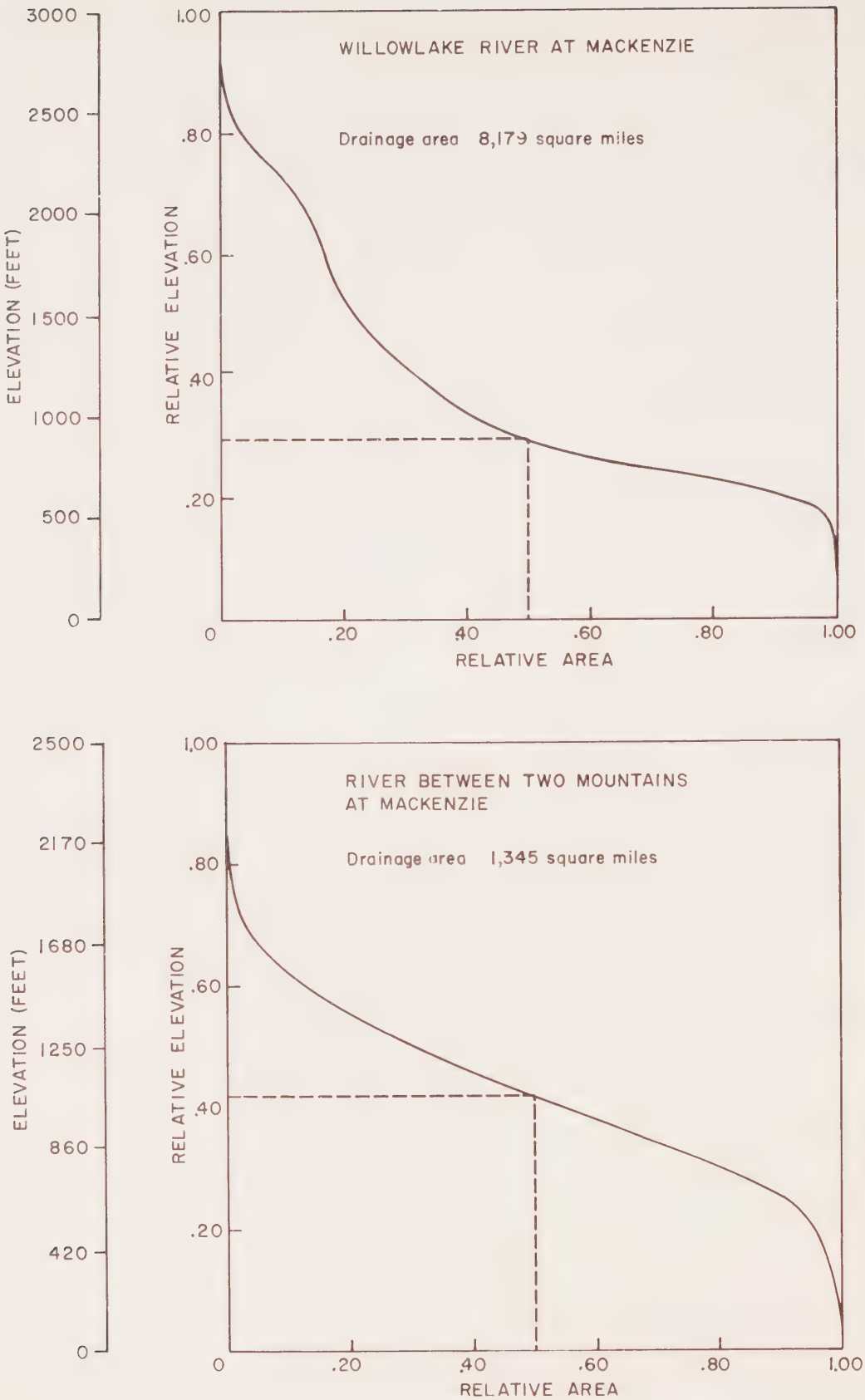
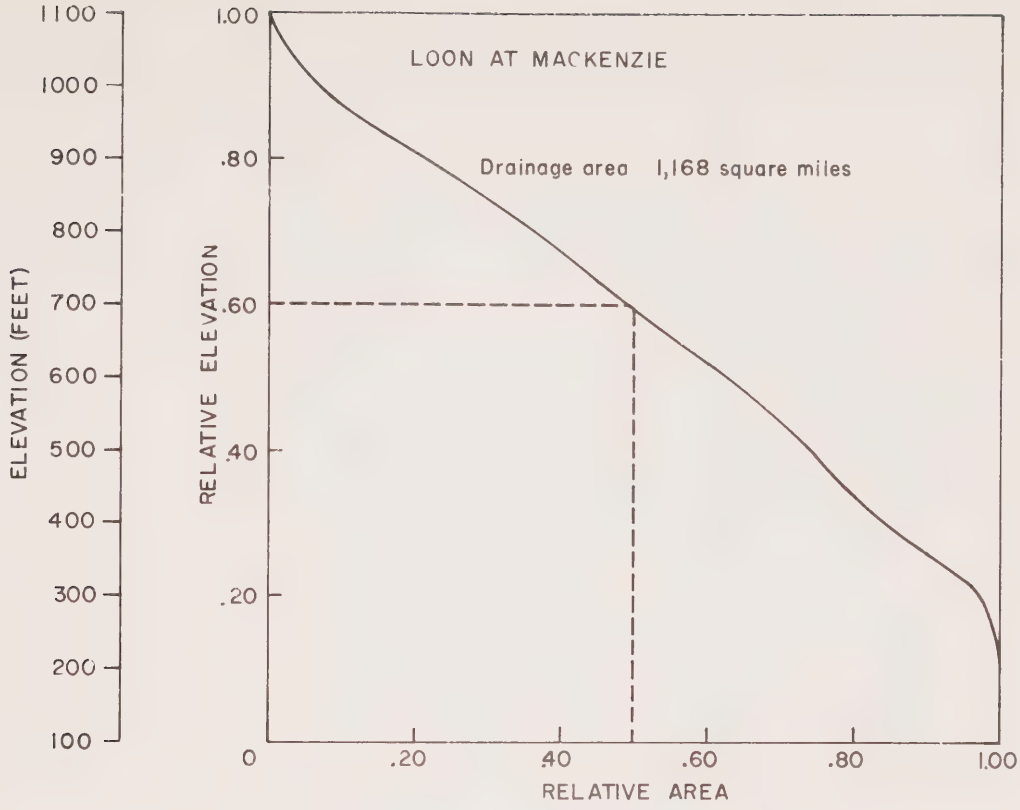


Figure 16. Hypsometric curves.



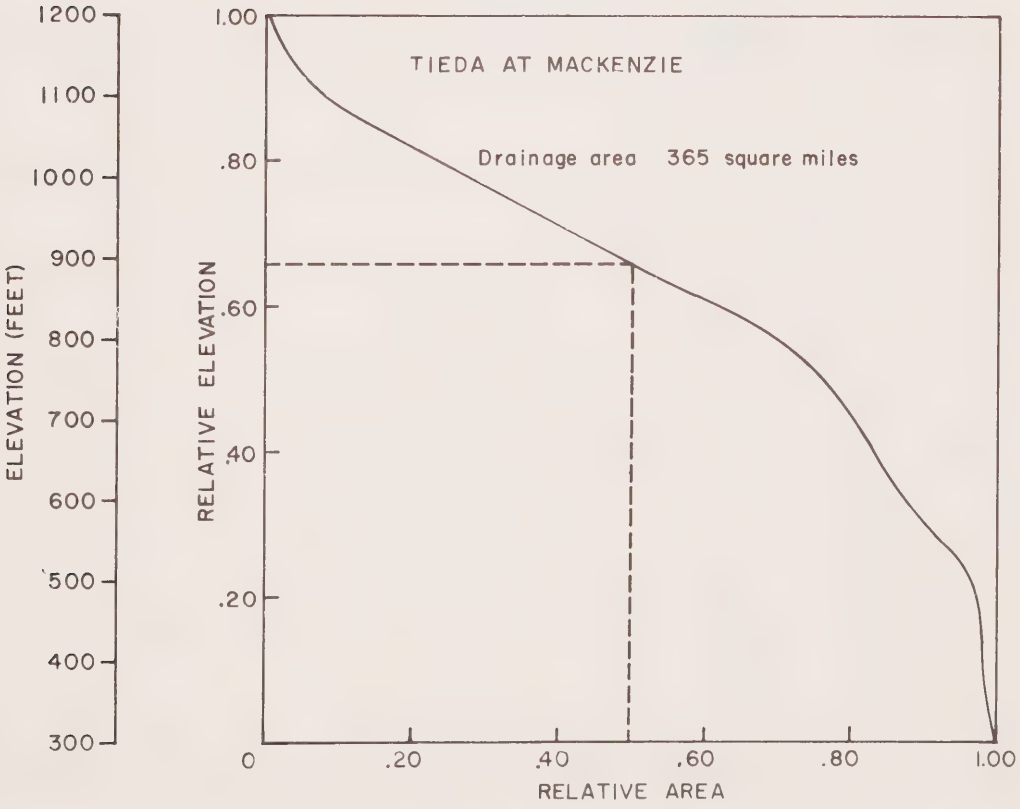
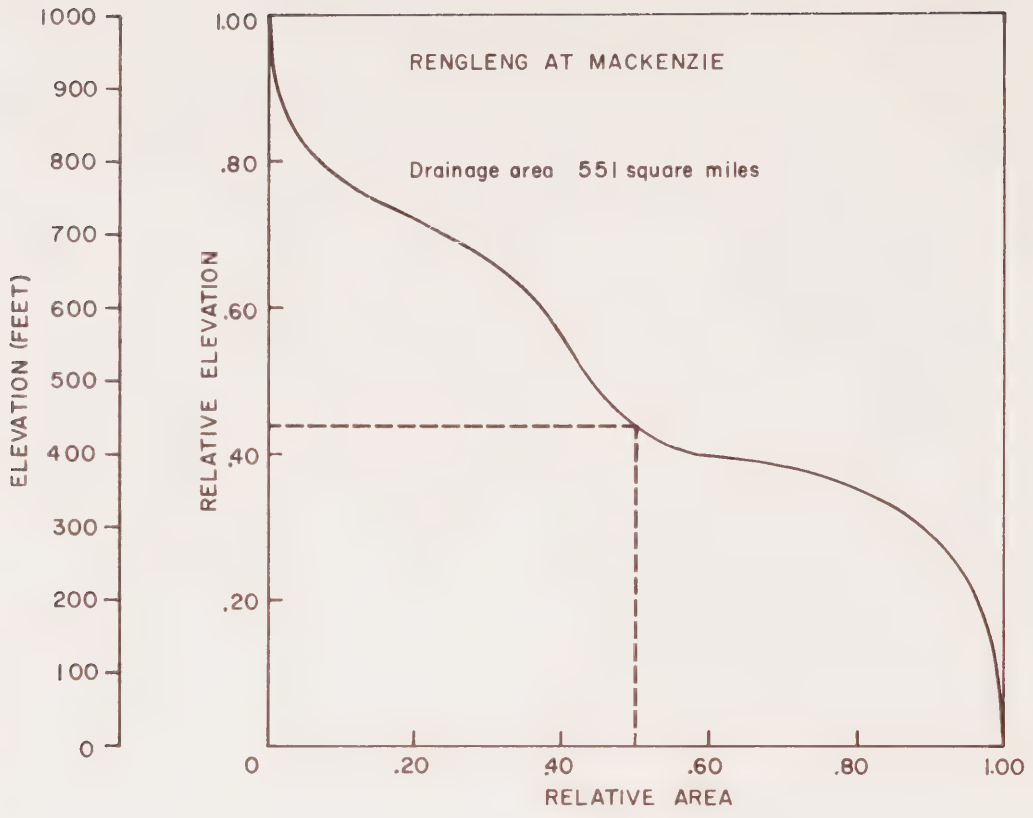


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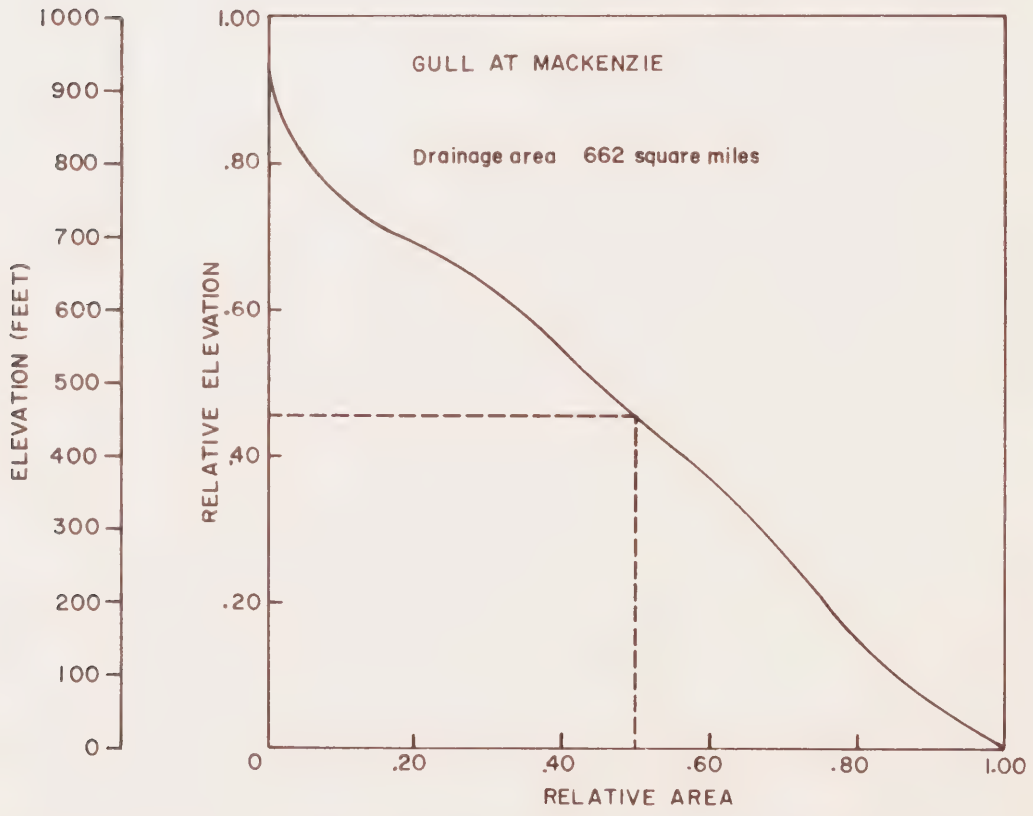
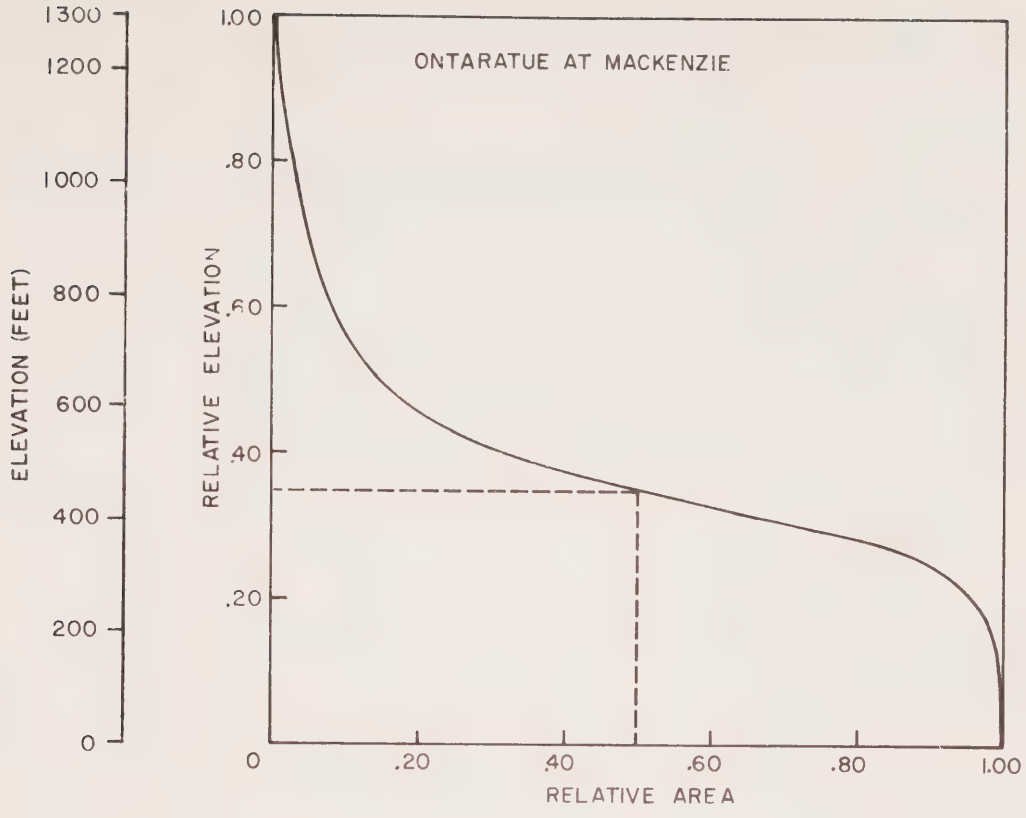


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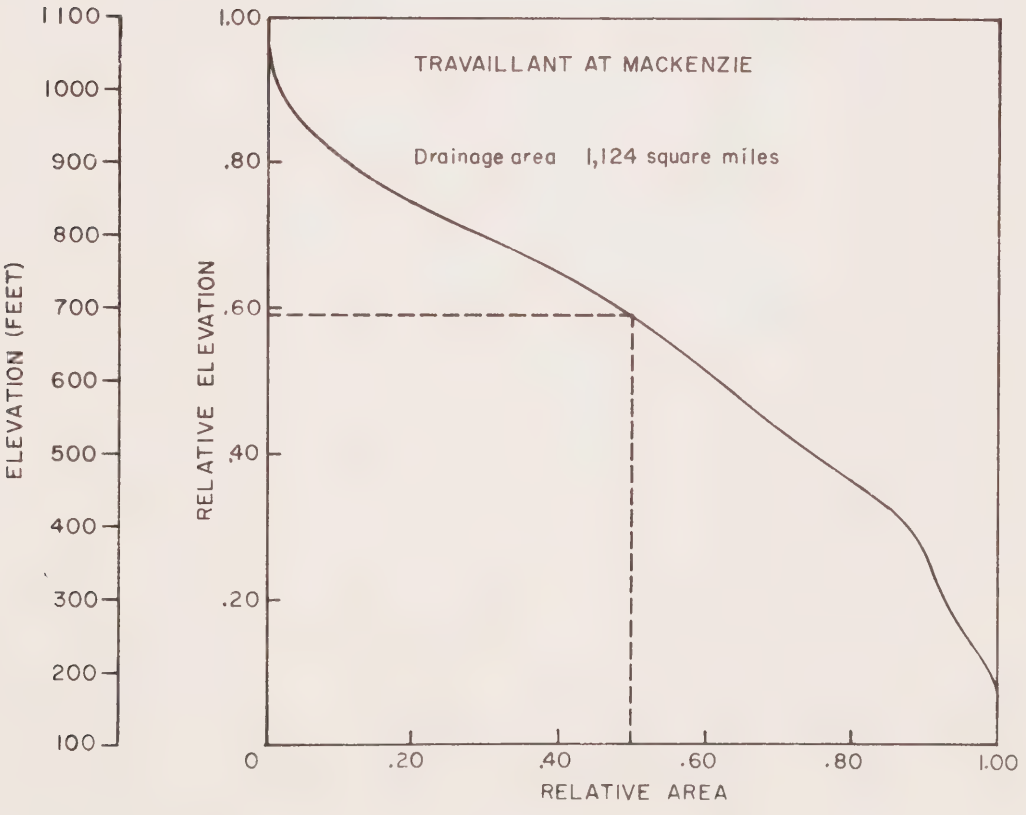
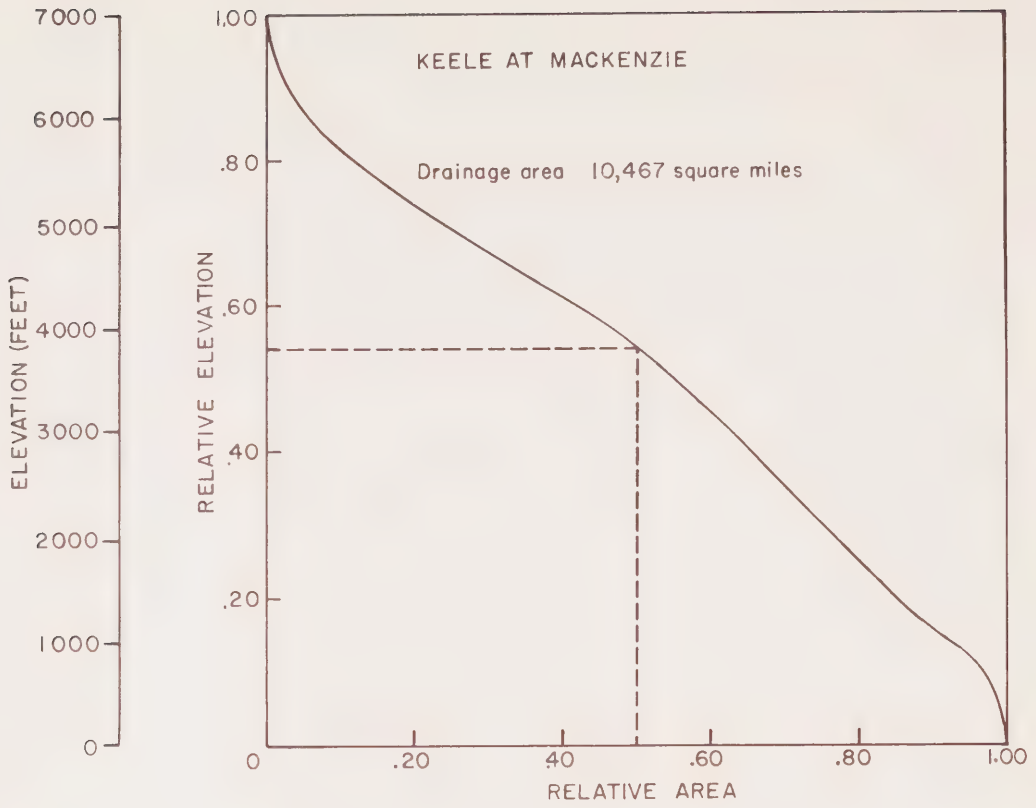


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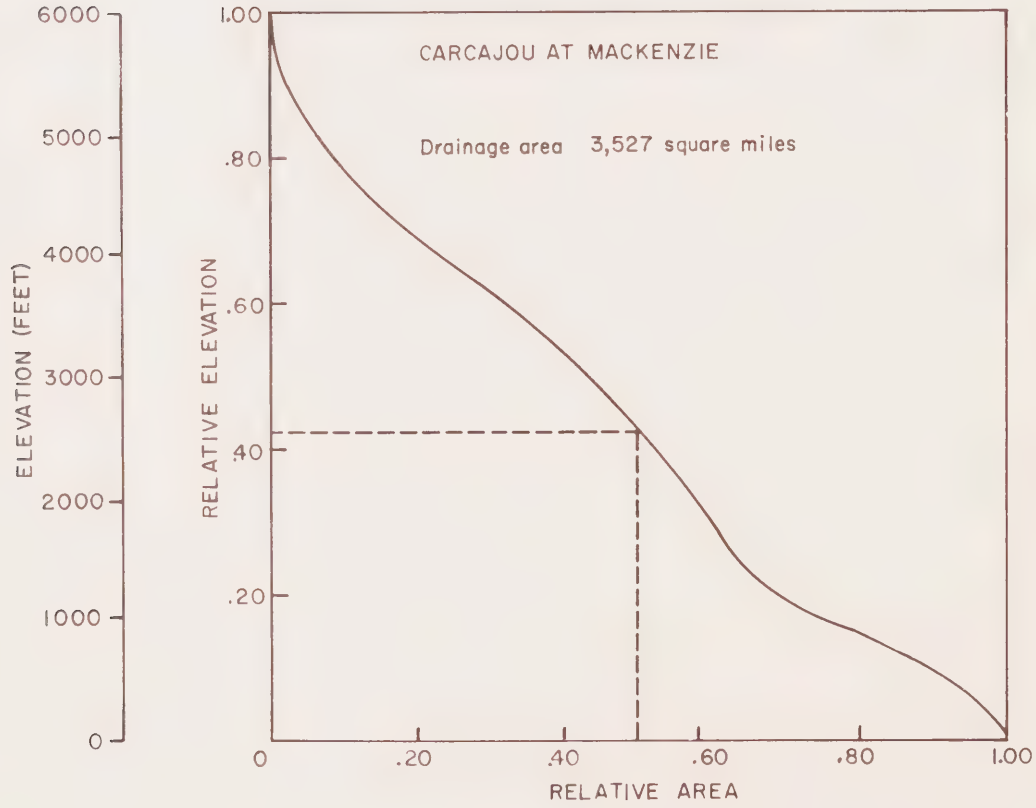
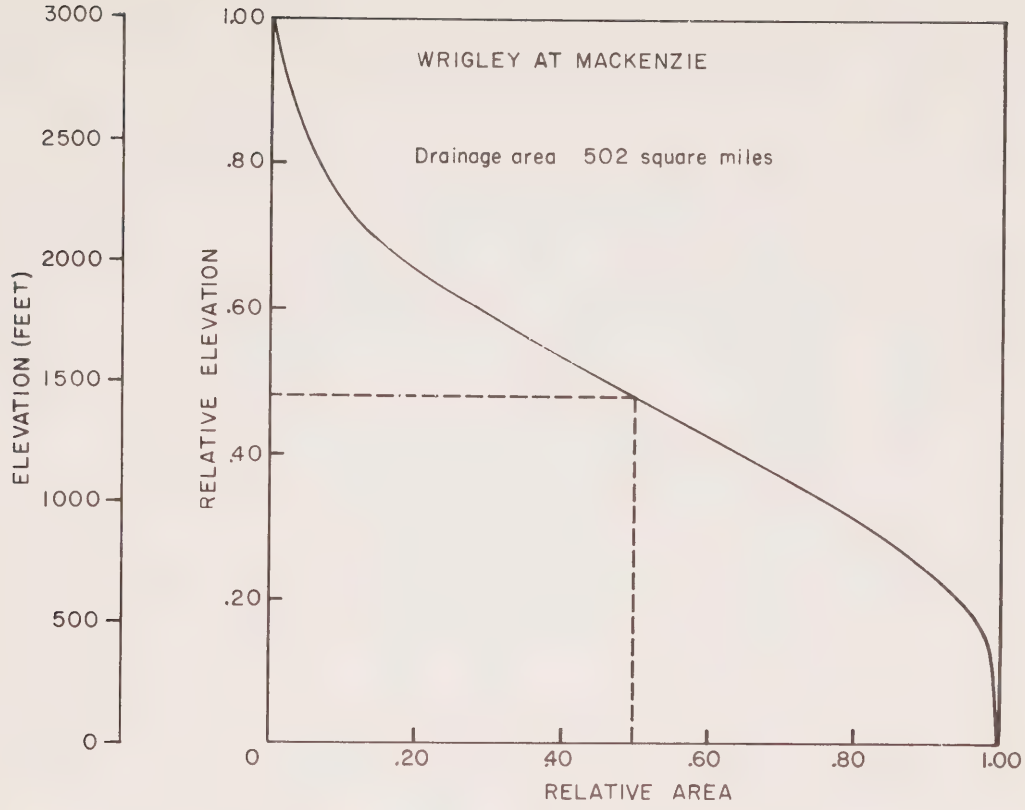


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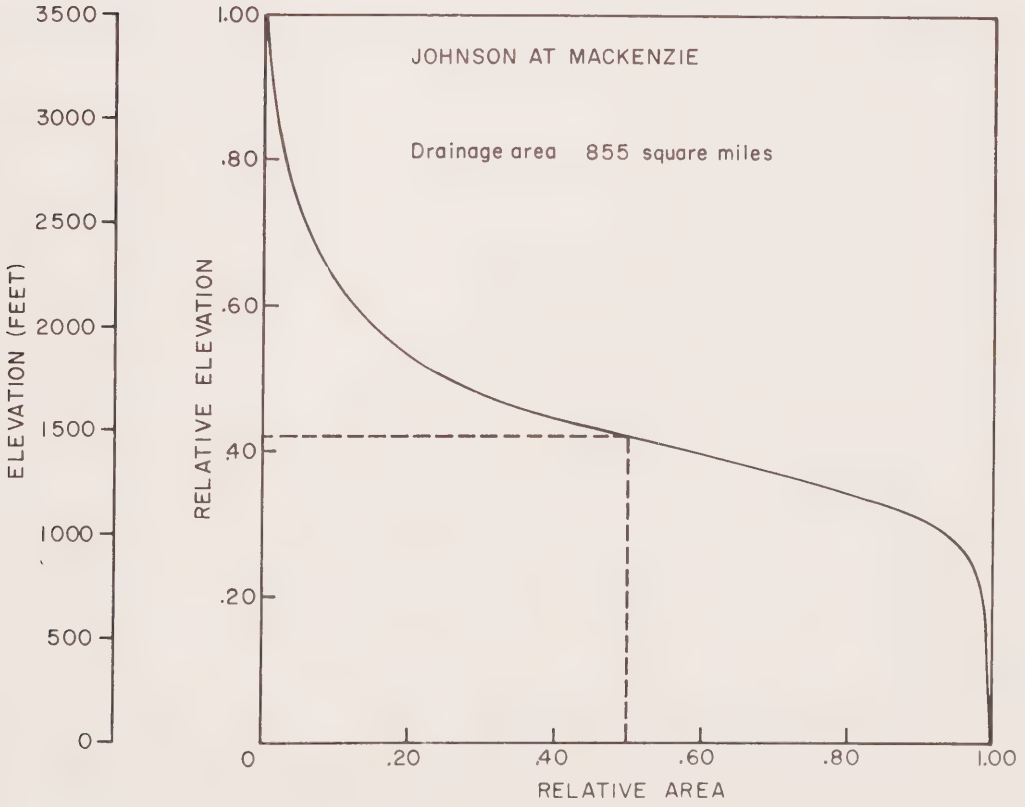
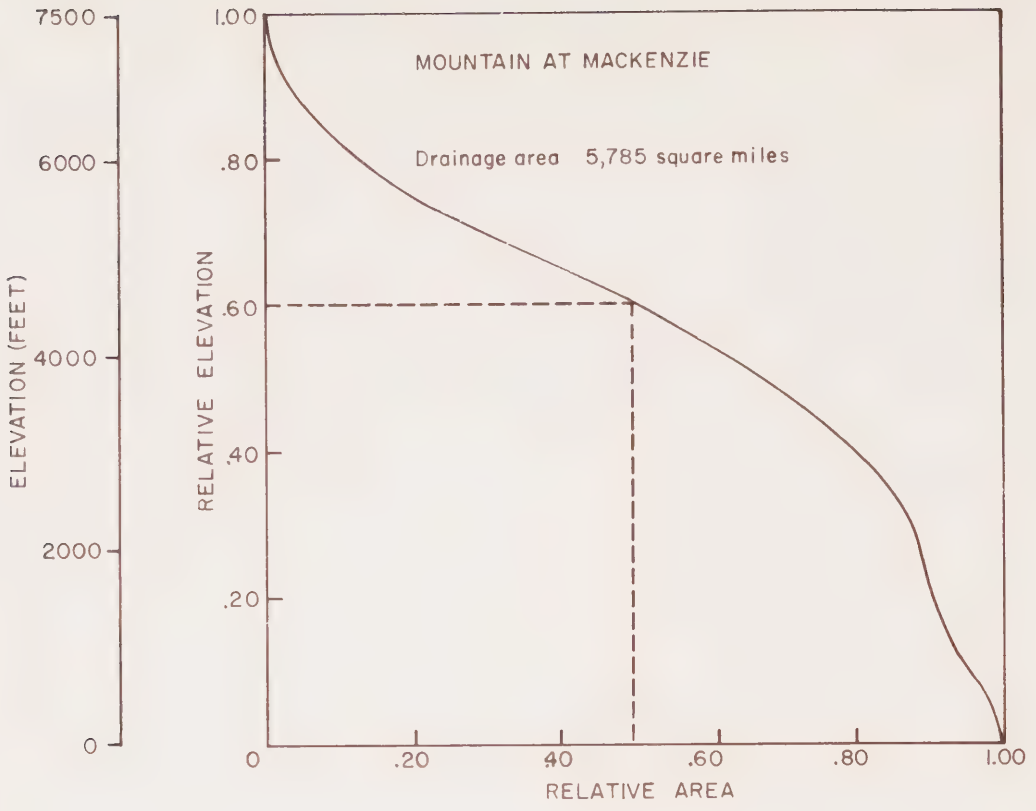


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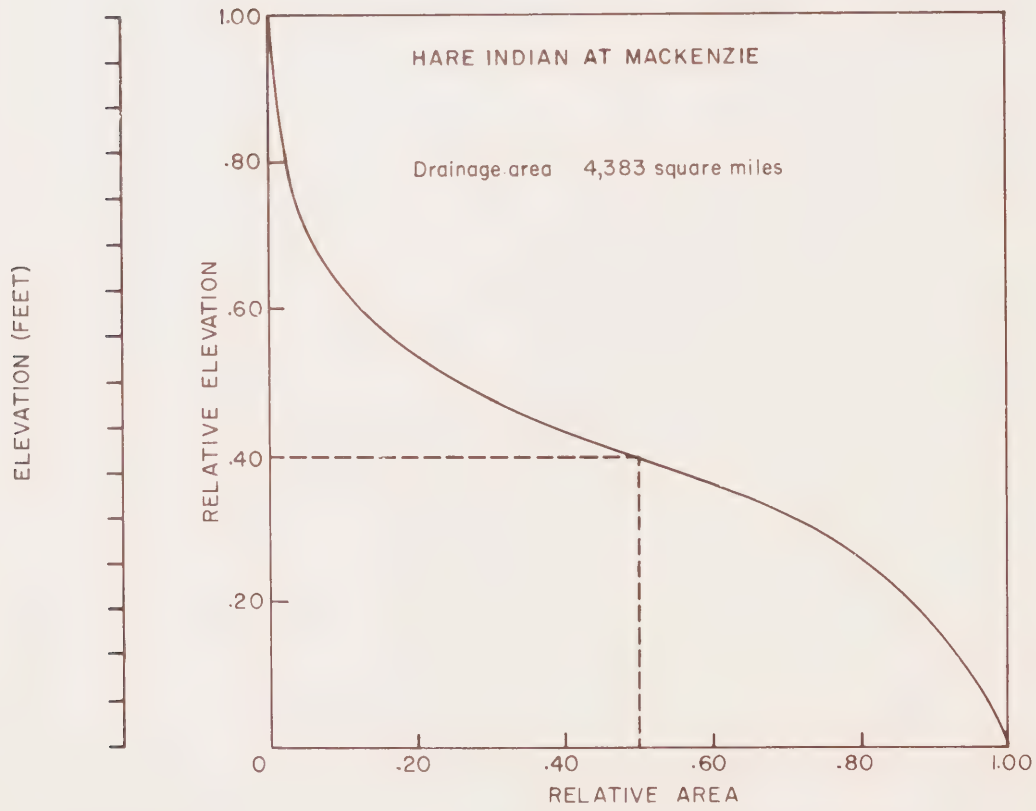
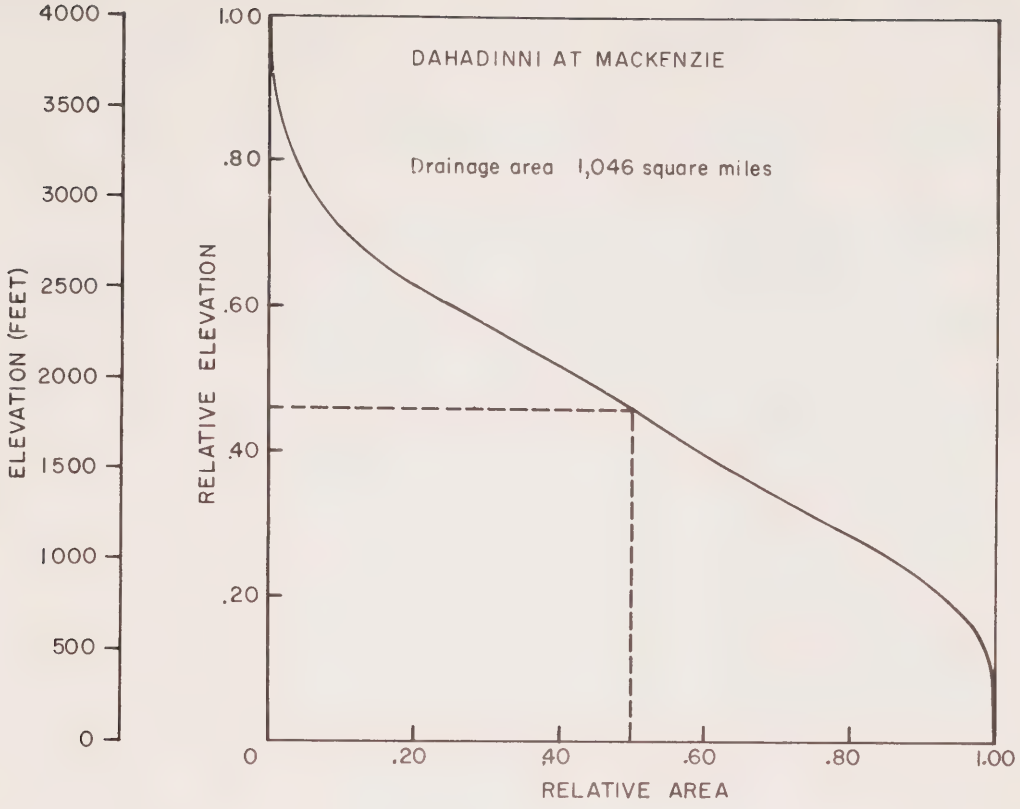


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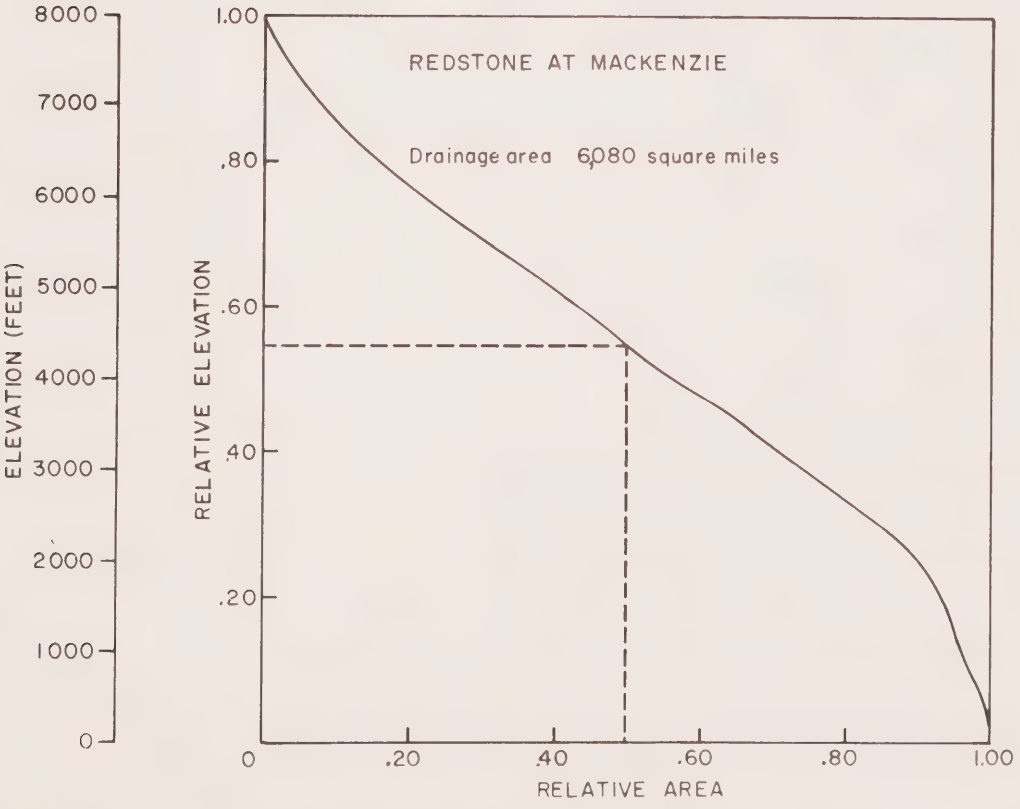
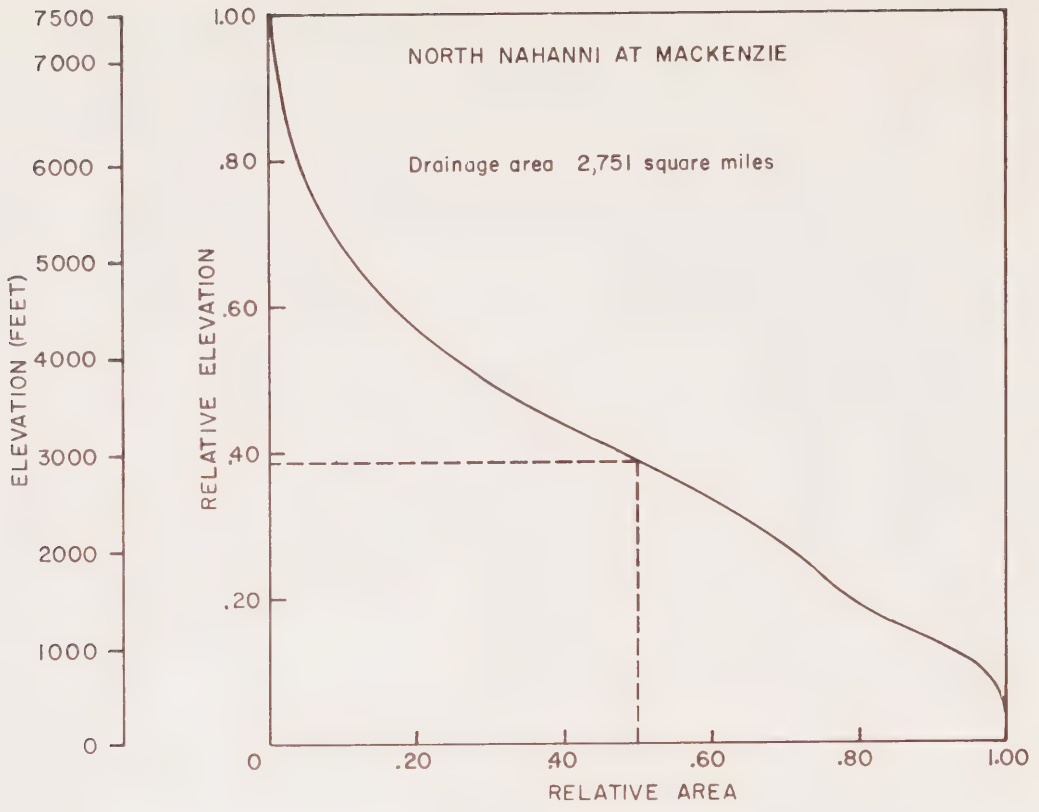


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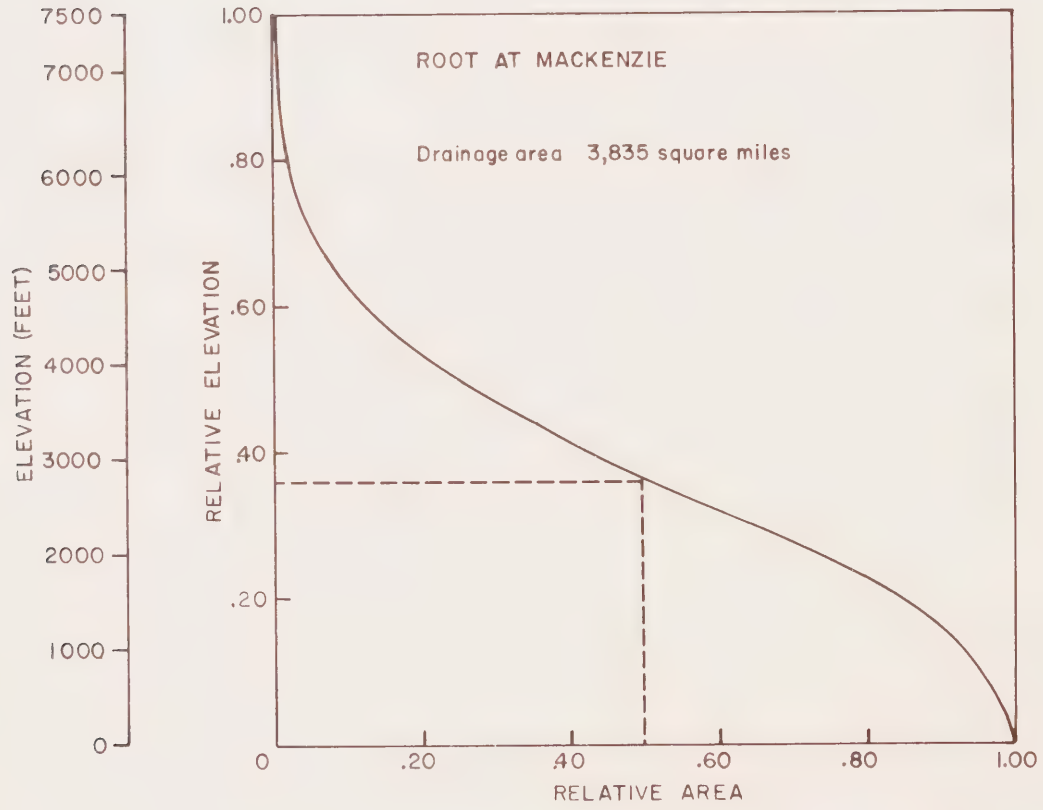
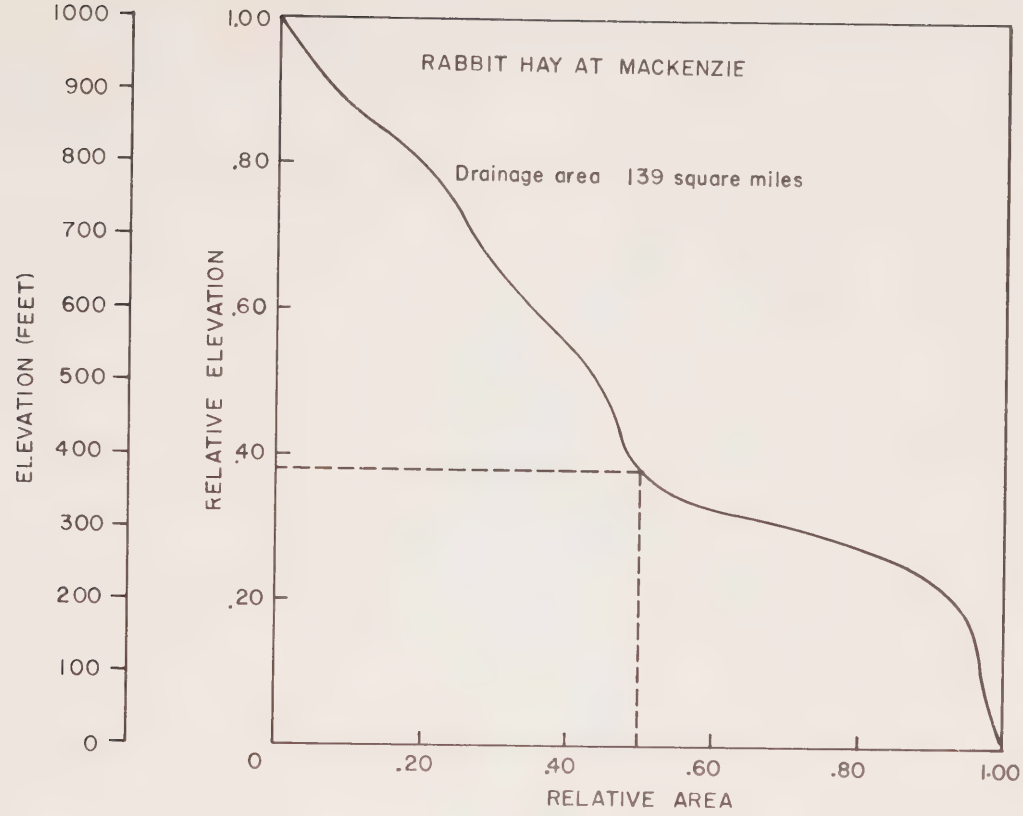


Figure 24. Hypsometric curves.



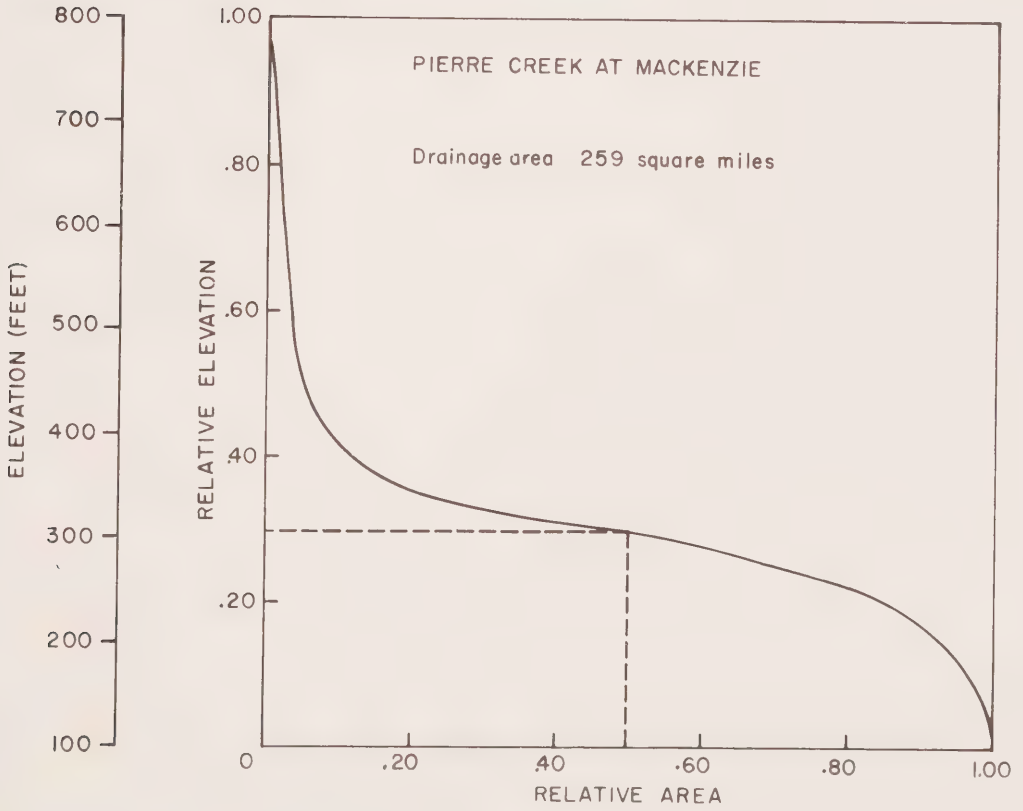
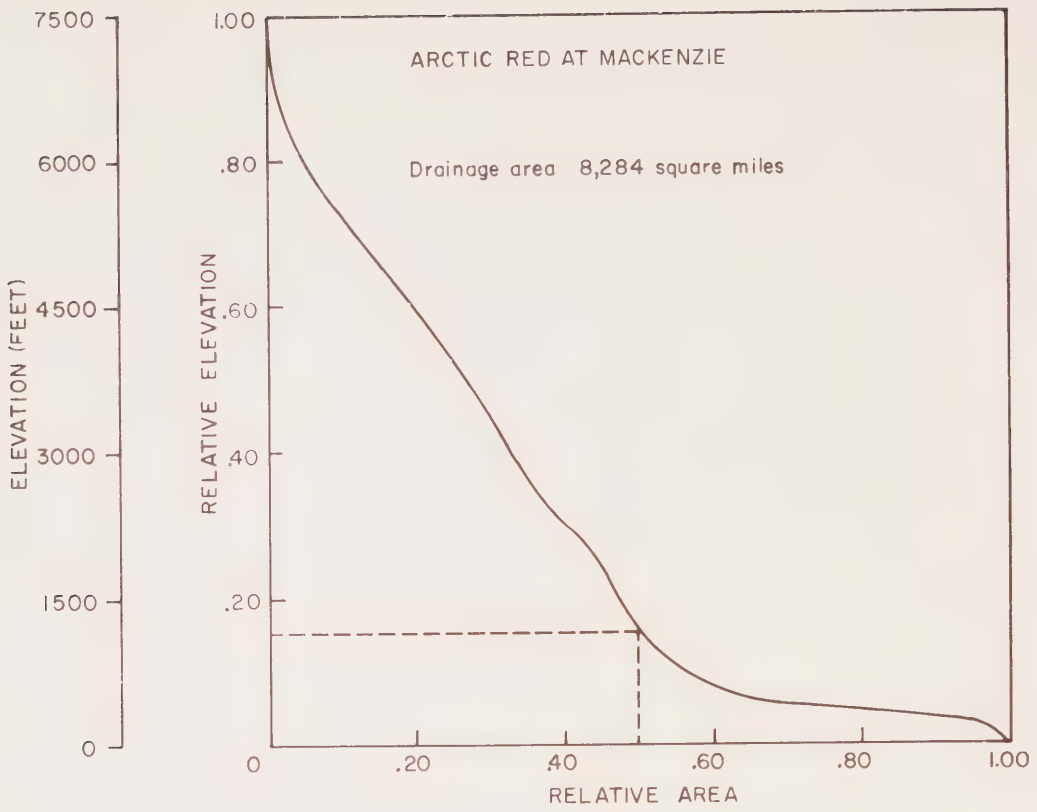


Figure 25. Hypsometric curves.



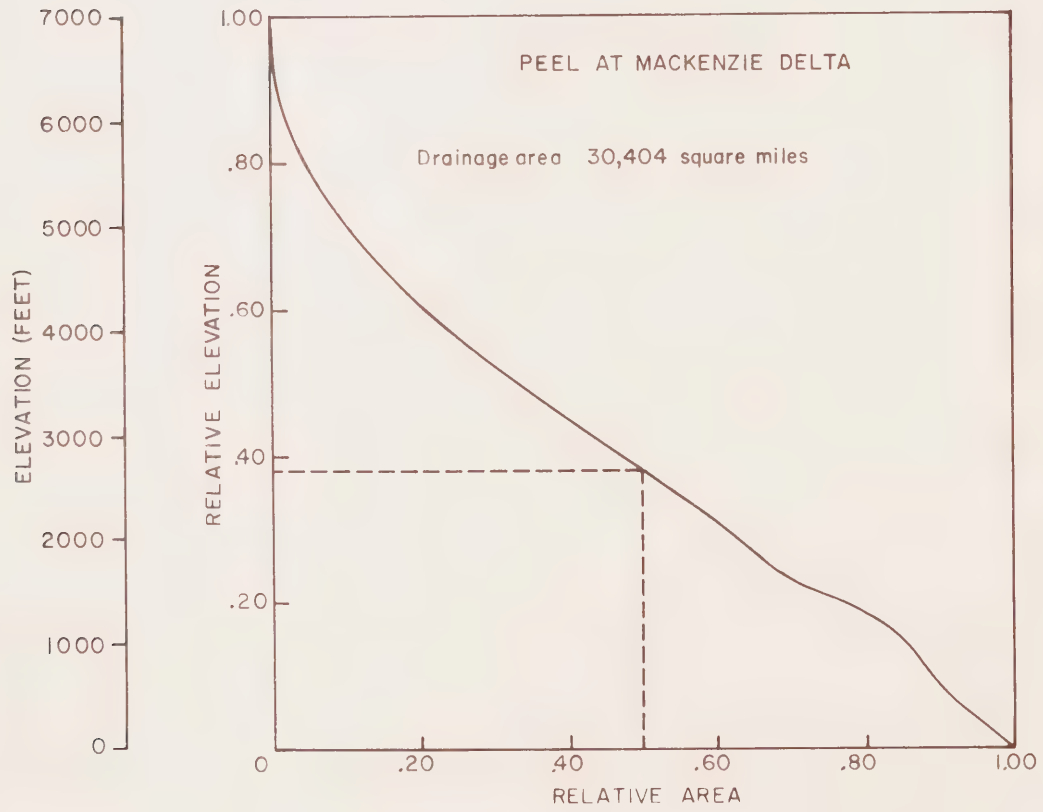
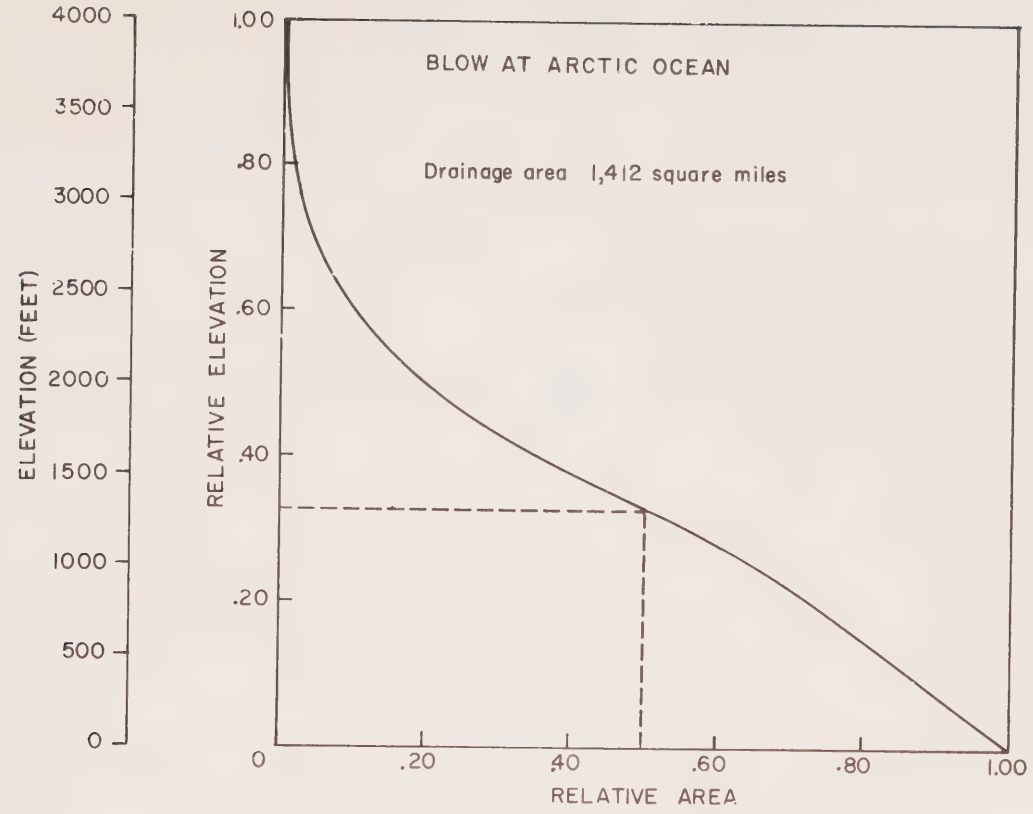


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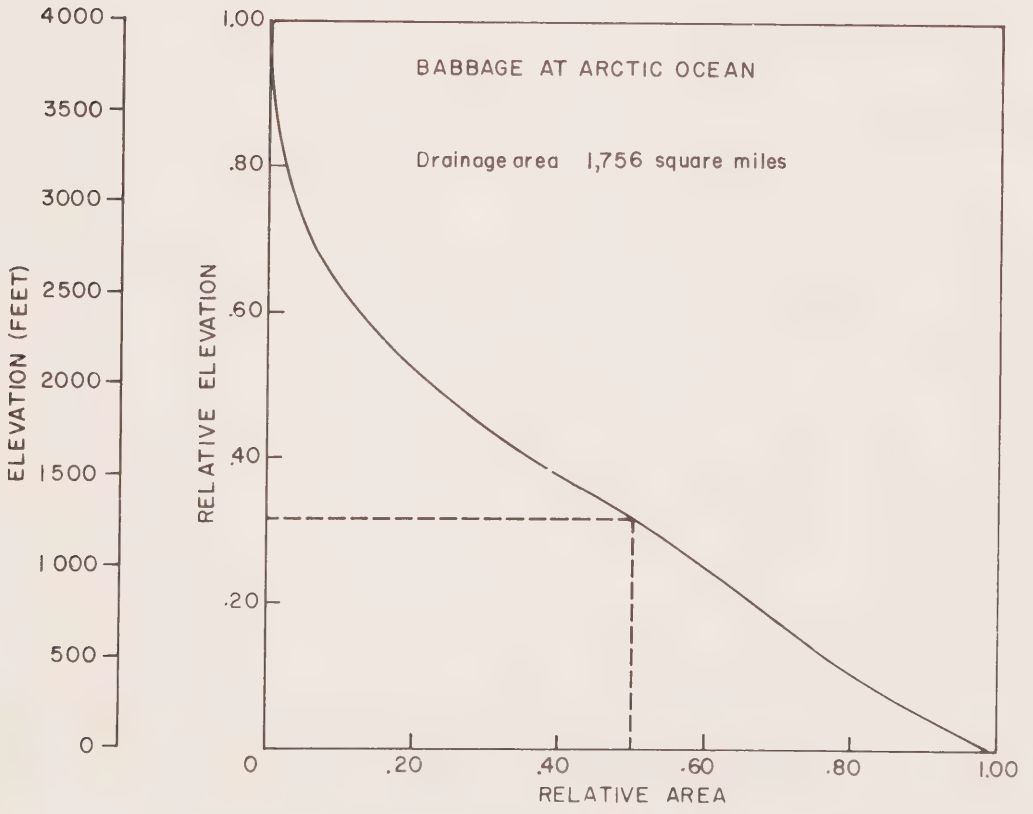
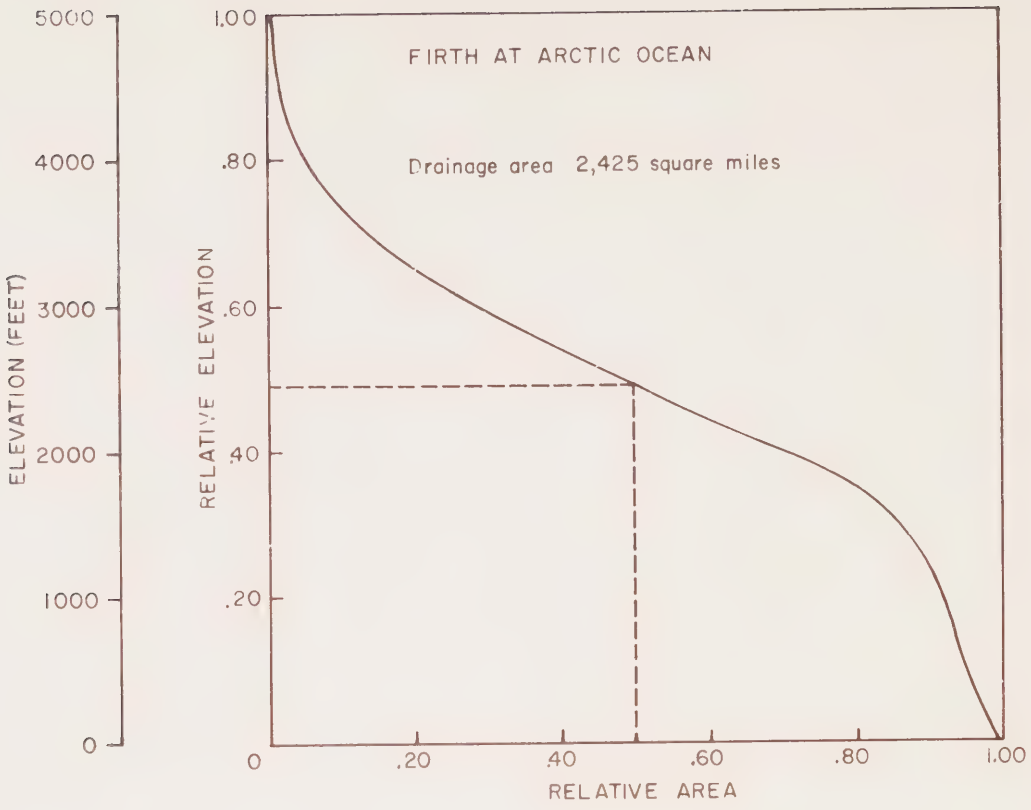


Figure 27. Hypsometric curves.



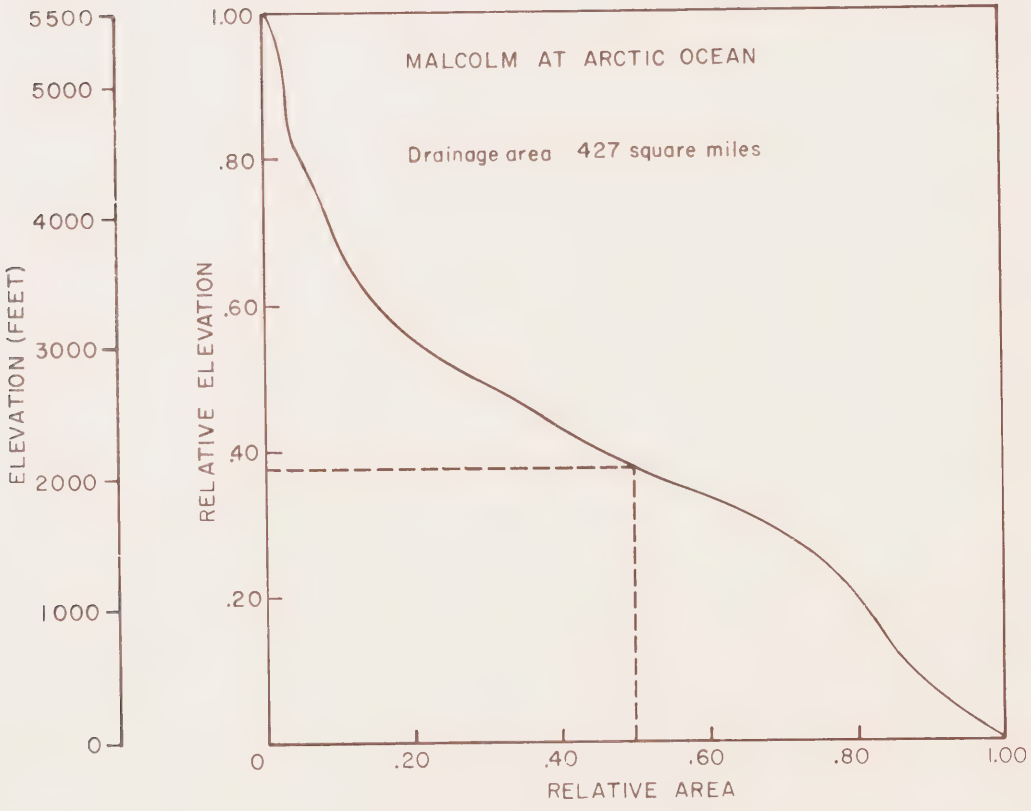


Figure 28. Hypsometric curves.

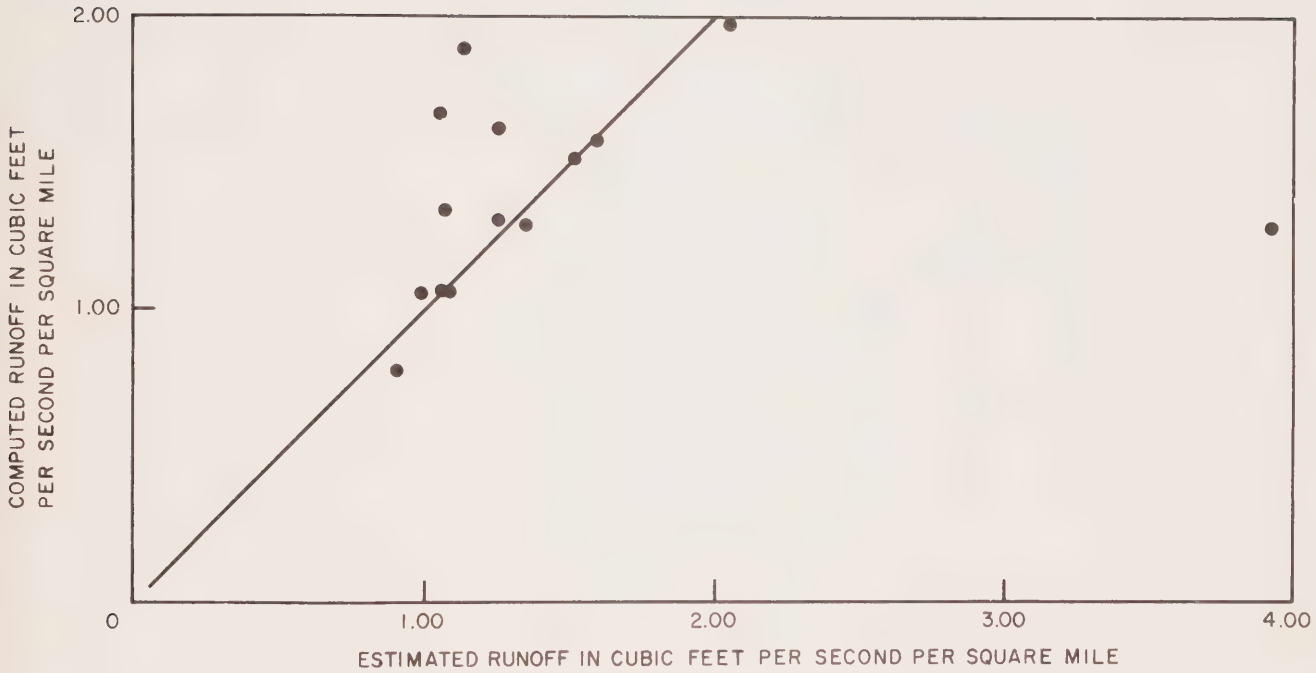


Figure 29. Mean annual flow - estimated runoff (from observed data of 14 gauged stations) versus computed runoff (from multiple regression equations).

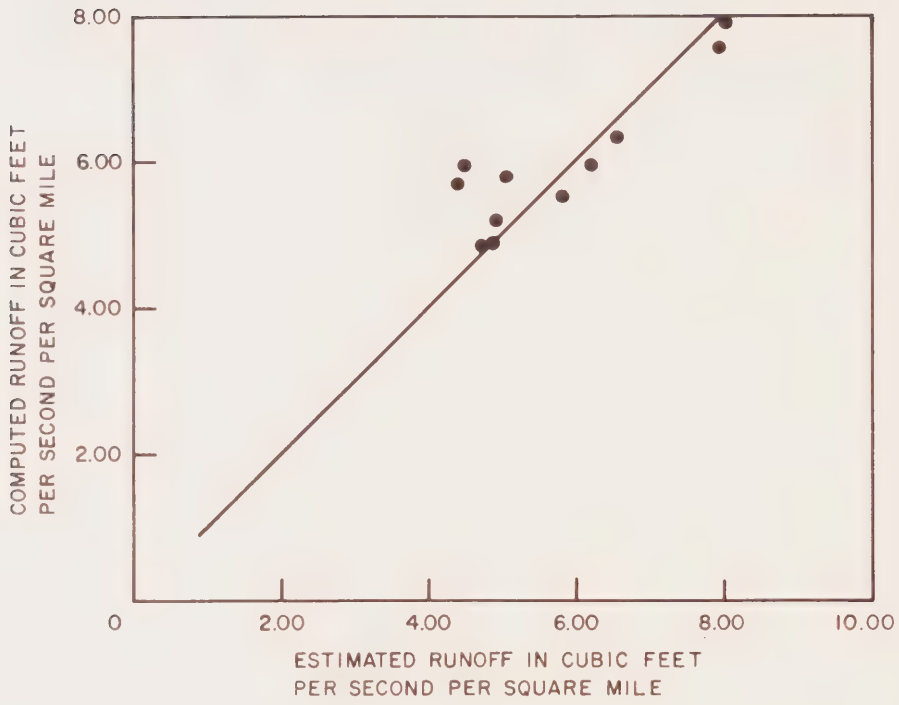


Figure 30. Mean annual flood - estimated runoff (from observed data of 11 gauged stations) versus computed runoff (from multiple regression equations).

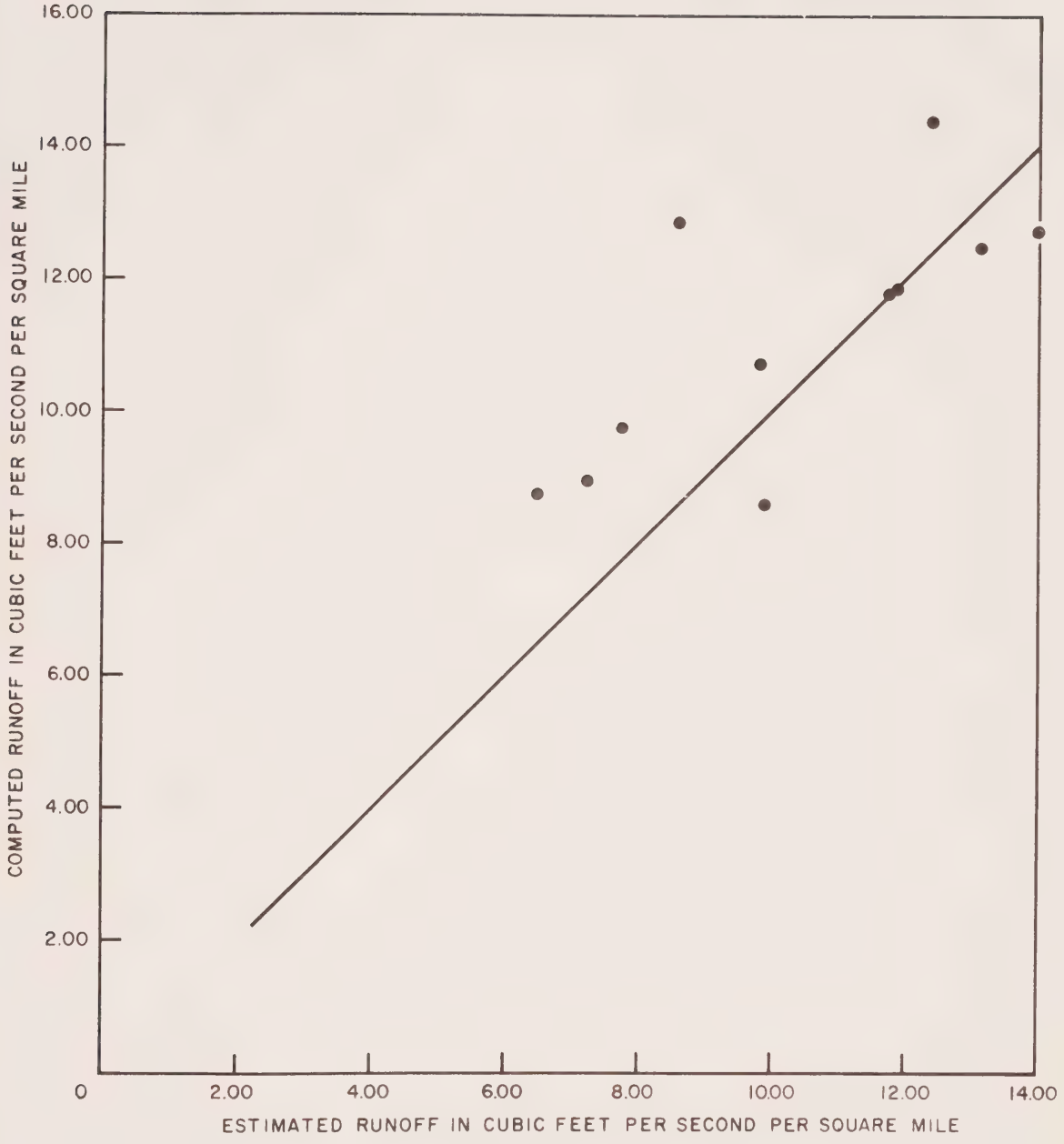


Figure 31. Mean annual 50 year flood - estimated runoff (from observed data of 11 gauged stations) versus computed runoff (from multiple regression equations).

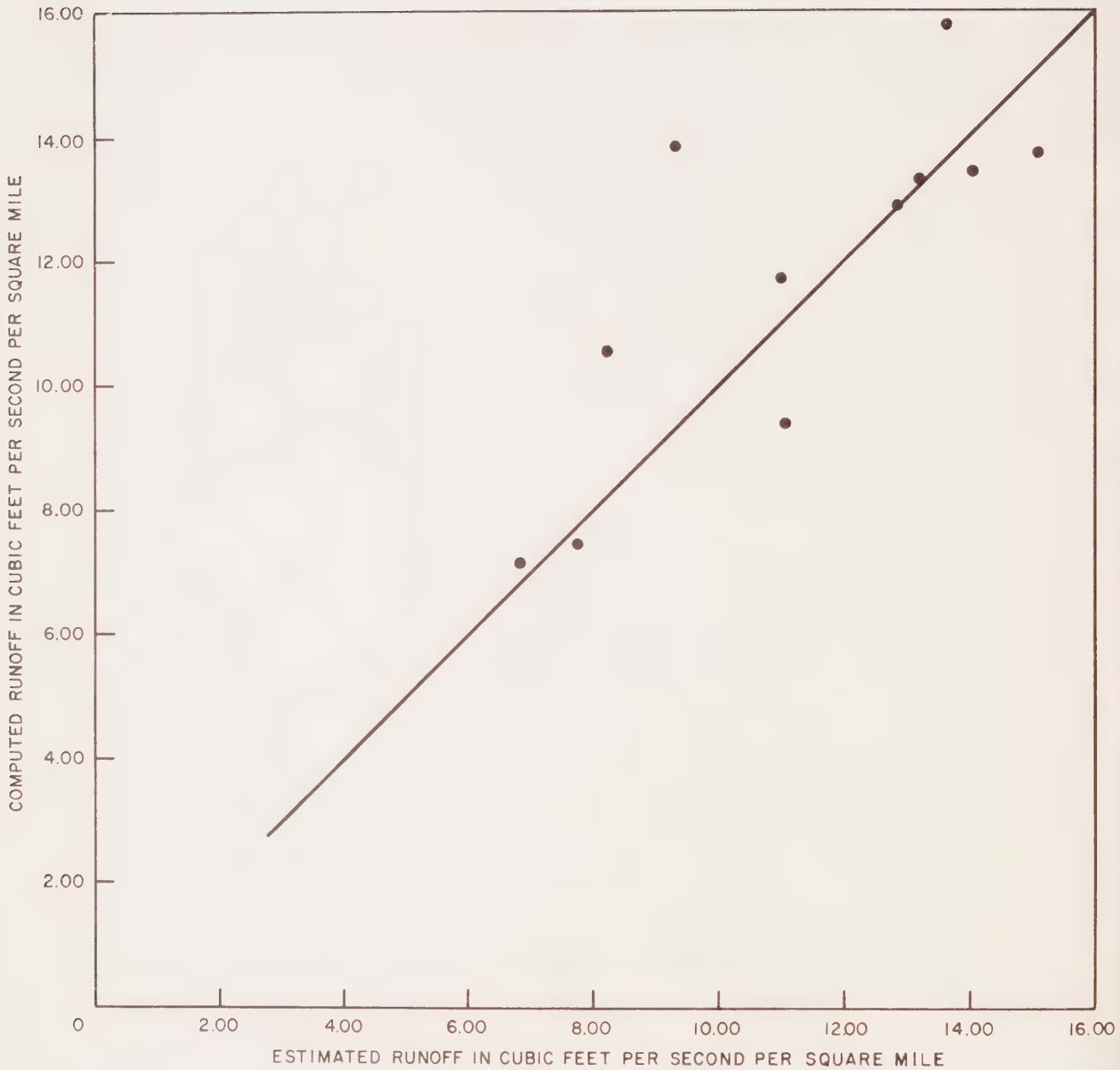


Figure 32. Mean annual 100 year flood - estimated runoff (from observed data of 11 gauged stations) versus computed runoff (from multiple regression equations).

APPENDIX 2

Table 9.	Morphometric data.
Table 10.	Computed hydrologic characteristics of 26 primary watersheds (multiple-regression analysis).
Table 11.	Estimated hydrologic characteristics of 14 gauged watersheds (flood-frequency analysis).
Table 12.	Comparison of computed and estimated hydrologic characteristics of 14 gauged watersheds.
Table 13.	Computed hydrologic characteristics of all watersheds under study (multiple-regression analysis).

Table 9. Morphometric data

SUBBASINS		DRAINAGE AREA (MILES^2)	MAXIMUM ELEVATION (FT)	MINIMUM ELEVATION (FT)	AVERAGE ELEVATION (FT)	MEAN ELEVATION (FT)	LONGITUDE	LATITUDE	HYPSOMETRIC COEFFICIENT	HYPSOMETRIC INTEGRAL	% AREA AT ELEVATION 0-2000 FT	% AREA AT ELEVATION 2000-4000 FT	% AREA AT ELEVATION 4000-6000 FT
Liard above Meister	10AA1	3639	5500	1750	3625	3960	130.8	60.9	-0.20	43.9	0.0	51.1	47.6
Meister at Liard	10AA2	805	5500	2221	3861	3976	130.7	60.4	-0.16	48.0	0.0	50.9	41.9
Rancheria at Liard	10AA3	2021	5500	2126	3813	4180	130.1	59.9	-0.12	48.0	0.0	44.0	52.5
Frances near Watson Lake	10AB001	4952	6500	2600	4550	3850	129.5	61.5	-0.05	43.3	0.0	55.0	43.0
Liard at Upper Crossing	10AA001	13675	5500	1750	3625	3665	130.4	60.5	-0.13	42.4	1.0	59.0	37.5
Dease at McDame	10AC002	2710	6400	2200	4300	4350	130.4	58.8	-0.35	51.5	0.0	28.0	68.0
Blue at Dease	10AC004	682	6600	1980	4290	4150	129.9	60.0	-0.18	50.3	0.1	45.9	39.0
Dease at Liard	10AC3	5754	4500	2000	3250	4361	129.5	59.3	-0.36	50.3	1.0	36.5	56.5
Hyland near Lower Post	10AD001	3424	7000	1900	4450	4380	128.6	61.0	-0.20	45.7	1.0	43.0	48.0
Turnagain at Kechika	10BA1	2696	7000	1750	4375	4570	128.2	58.6	-0.37	51.6	0.5	29.0	61.5
Turnagain at Guaging Station	10BA001	2519	7000	2050	4525	4684	128.2	58.6	-0.24	47.5	0.0	28.0	62.8
Kechika above Boya Creek	10BB002	4249	6250	1940	4095	4640	126.2	58.3	-0.27	48.6	0.5	33.8	50.3
Kechika at Liard	10BB001	8533	6250	1750	4000	4291	127.1	58.4	-0.22	43.1	2.0	39.8	48.2
Coal at Liard	10BC001	3620	7000	1750	4375	3490	127.4	60.7	-0.27	43.3	1.0	69.0	27.8
Beaver at Liard	10BD1	4184	4550	750	2650	3180	125.4	60.4	-0.47	57.3	14.2	74.6	11.2
Flat at S. Nahanni	10EA003	3326	7400	1500	4450	2660	126.5	61.5	-0.30	40.3	1.0	43.0	47.0
S. Nahanni above Virginia Falls	10EB001	5653	7800	1500	4650	5140	128.0	63.0	-0.42	50.0	1.0	27.0	53.0
Root at Mackenzie	10GA1	3835	7500	250	3875	2770	124.8	62.5	-0.12	38.1	26.0	52.4	19.5
Willowlake River at Mackenzie	10GB2	8179	1100	250	675	894	120.2	62.7	-0.07	37.9	85.4	14.6	0.0
River Between Two Mountains at Mackenzie	10GB1	1345	1300	250	775	1045	122.5	63.1	-0.44	43.2	99.0	1.01	0.0
N. Nahanni at Mackenzie	10GD1	2751	7500	250	3875	3599	124.5	62.0	-0.36	48.3	12.2	49.8	30.7
Ram at N. Nahanni	10GD2	1149	4550	300	2425	2877	124.4	61.8	-0.26	45.6	13.8	65.2	21.0
Tetcela at N. Nahanni	10GD3	1509	2775	275	1525	1370	123.5	61.6	+0.64	25.5	70.6	24.9	4.5
Keele at Mackenzie	10HA1	10467	5750	250	3000	4464	128.4	63.8	-0.38	57.8	16.8	22.7	52.0
Dahadinni at Mackenzie	10HB1	1046	3500*	250	1875	1815	125.0	63.5	-0.29	41.4	56.7	42.8	0.0
Johnson at Mackenzie	10HB2	855	4000	250	2125	1484	124.4	63.4	-0.51	39.8	84.8	15.2	0.0
Wrigley at Mackenzie	10HB3	502	2500	250	1375	1440	123.7	63.2	-0.33	48.9	82.0	18.0	0.0

* Underlined values are estimated

SUBBASINS		% AREA AT 6000 FT ELEVATION AND OVER	% AREA ABOVE AVERAGE ELEVATION	% LAKE AND SWAMP	% FOREST	% GLACIER	CIRCULATORY RATIO	ELONGATION RATIO	RELIEF RATIO X 100	WEIGHTED MEAN BIFURCATION RATIO	LENGTH RATIO	AREA RATIO	DRAINAGE DENSITY (Miles miles^{-2})
Liard above Meister	10AA1	1.3	38.8	5.7	78.6	0.0	0.530	0.613	0.56	3.97	2.25	4.72	1.051
Meister at Liard	10AA2	0.0	49.5	4.0	71.2	0.0	0.476	0.471	0.91	3.96	2.26	5.13	0.759
Rancheria at Liard	10AA3	3.5	47.0	6.9	54.8	0.0	0.466	0.625	0.80	4.91	1.99	4.03	0.773
Frances near Watson Lake	10AB001	2.0	31.0	5.7	70.4	0.1	0.523	0.601	0.64	3.95	2.22	5.60	0.850
Liard at Upper Crossing	10AB001	2.5	33.3	4.4	51.8	0.0	0.372	0.714	0.38	3.95	2.14	4.70	0.879
Dease at McDame	10AC002	4.0	62.0	1.1	51.1	0.0	0.559	0.875	1.27	4.28	1.97	4.04	0.777
Blue at Dease	10AC004	15.0	47.0	8.4	64.2	0.0	0.581	0.577	1.48	4.04	2.24	6.65	0.784
Dease at Liard	10AC3	6.0	52.7	4.9	60.3	0.0	0.611	0.713	0.71	4.07	2.29	4.89	0.748
Hyland near Lower Post	10AD001	8.0	41.0	3.9	71.4	0.2	0.420	0.411	0.59	4.06	1.97	4.89	0.968
Turnagain at Kechika	10BA1	9.0	53.6	2.2	25.9	0.0	0.513	0.523	0.89	3.95	2.39	5.81	0.818
Turnagain at Gauging Station	10BA001	9.2	48.0	2.1	22.2	0.0	0.531	0.566	0.94	4.00	2.29	5.59	0.805
Kechika above Boya Creek	10BB002	15.4	47.5	1.7	57.8	1.3	0.450	0.759	0.84	3.85	2.06	4.27	0.721
Kechika at Liard	10BB001	10.0	39.8	2.8	63.9	0.7	0.364	0.693	0.57	3.78	2.28	5.31	0.788
Coal at Liard	10BC001	2.2	30.0	3.6	86.5	0.0	0.474	0.500	0.71	3.71	2.29	5.45	1.044
Beaver at Liard	10BD1	0.0	66.8	1.3	96.7	0.0	0.536	0.629	0.62	4.19	1.94	4.59	0.733
Flat at S. Nahanni	10EA003	9.0	42.0	1.6	70.5	0.6	0.510	0.618	1.11	4.04	2.03	5.33	0.913
S. Nahanni above Virginia Falls	10EC001	19.0	60.0	0.7	31.0	2.7	0.527	0.524	0.72	4.19	1.92	5.27	0.849
Root at Mackenzie	10GA1	2.1	25.0	1.0	63.0	0.0	0.619	0.636	1.21	4.31	1.90	4.05	0.858
Willowlake R. at Mackenzie	10GB1	0.0	21.5	26.3	88.9	0.0	0.557	0.676	0.36	3.91	2.16	5.40	0.659
River between Two Mountains at Mackenzie	10GB1	0.0	30.0	8.8	90.7	0.0	0.710	0.845	1.23	4.41	1.80	5.05	0.599
N. Nahanni at Mackenzie	10GD1	7.3	37.5	0.6	54.1	0.0	0.508	0.537	1.27	4.28	1.77	3.62	0.862
Ram at N. Nahanni	10GD2	0.0	37.5	3.7	71.6	0.0	0.785	0.792	1.68	3.92	1.76	3.20	1.048
Tetcela at N. Nahanni	10GD3	0.0	14.5	14.9	76.2	0.0	0.716	0.786	0.85	4.26	2.06	6.00	0.932
Keele at Mackenzie	10HA1	8.5	68.0	1.2	36.7	0.1	0.463	0.529	0.48	3.97	2.00	4.17	0.856
Dahadinni at Mackenzie	10HB1	0.0	31.0	4.5	94.6	0.0	0.538	0.521	0.96	3.84	1.78	4.68	0.873
Johnson at Mackenzie	10HB2	0.0	15.2	7.6	91.1	0.0	0.702	0.694	1.35	5.13	2.06	3.56	0.880
Wrigley at Mackenzie	10HB3	0.0	46.4	2.2	96.3	0.0	0.785	1.040	1.89	3.93	1.73	3.74	0.894

Table 9 (Cont'd). Morphometric data

SUBBASINS		STREAM FREQUENCY	85-10 SLOPE FACTOR	CONSTANT OF CHANNEL MAINTENANCE (FT)	MAIN CHANNEL LENGTH (MILES)	DIRECT DISTANCE FROM MOUTH TO HEAD (MILES)	SINUOSITY RATIO	STREAM ORDER	PERIMETER (MILES)	HYDROLOGIC DATA	TOPOGRAPHIC MAP SCALE
Liard above Meister	10AA1	0.668	9.0	5024	155	111	1.40	6	403	NO	
Meister at Liard	10AA2	0.333	24.8	6957	95	68	1.40	5	211	NO	
Rancheria at Liard	10AA3	0.323	14.0	6831	124	80	1.55	6	337	NO	
Frances near Watson Lake	10AB001	0.513	3.0	6250	155	133	1.17	6	480	YES	
Liard at Upper Crossing	10AA001	0.419	7.8	6007	204	148	1.38	7	609	YES	
Dease at McDame	10AC002	0.457	2.0	6800	88	67	1.31	6	329	YES	
Blue at Dease	10AC004	0.483	2.9	6740	65	51	1.27	5	159	YES	
Dease at Liard	10AC3	0.449	2.3	7050	178	120	1.48	6	440	NO	
Hyland near Lower Post	10AD001	0.559	5.8	5500	222	154	1.44	6	498	YES	
Turnagain at Kechika	10BA1	0.133	13.5	6455	150	112	1.34	5	359	NO	
Turnagain at Gauging Station	10BA001	0.275	13.5	6559	134	100	1.34	5	352	YES	
Kechika above Boya Creek	10BB002	0.310	11.2	7184	119	97	1.23	6	383	YES	1: 250,000
Kechika at Liard	10BB001	0.333	6.8	6701	194	150	1.29	6	562	YES	
Coal at Liard	10BC001	0.469	10.2	5057	256	140	1.83	6	464	YES	
Beaver at Liard	10BD1	0.261	12.4	7203	180	116	1.55	6	428	NO	
Flat at S. Nahanni	10EA003	0.554	13.7	5780	150	105	1.43	7	400	YES	
S. Nahanni above Virginia Falls	10EB001	0.376	10.3	6280	200	162	1.23	6	578	YES	
Root at Mackenzie	10GA1	0.316	21.8	6154	149	110	1.35	6	355	NO	
Willowlake at Mackenzie	10GB2	0.448	2.7	10887	252	151	1.67	6	575	NO	
River Between Two Mountains at Mackenzie	10GB1	0.448	11.8	10252	88	49	1.80	5	183	NO	1: 250,000
N. Nahanni at Mackenzie	10GD1	0.335	23.0	6125	166	108	1.54	7	371	NO	
Ram at N. Nahanni	10GD2	0.434	35.7*	5038	92	48	1.92	6	152	NO	
Tetcela at N. Nahanni	10GD3	0.221	9.5	6658	119	56	2.13	5	193	NO	
Keele at Mackenzie	10HA1	0.518	14.0	6168	262	218	1.20	7	783	NO	
Dahadinni at Mackenzie	10HB1	0.313	25.6	6048	127	69	1.84	5	210	NO	
Johnson at Mackenzie	10HB2	0.315	43.6	6000	86	49	1.76	5	152	NO	
Wrigley at Mackenzie	10HB3	0.353	43.3	5906	52	25	2.08	5	104	NO	

* Underlined values are estimated

SUBBASINS		DRAINAGE AREA ($MILES^2$)	MAXIMUM ELEVATION (FT)	MINIMUM ELEVATION (FT)	AVERAGE ELEVATION (FT)	MEAN ELEVATION (FT)	LONGITUDE	LATITUDE	HYPSOMETRIC COEFFICIENT	HYPSOMETRIC INTEGRAL	% AREA AT ELEVATION 0-2000 FT	% AREA AT ELEVATION 2000-4000 FT	% AREA AT ELEVATION 4000-6000 FT
Redstone at Mackenzie	10HB001	6080	7000	250	3625	4252	126.7	63.3	-0.30	54.4	9.6	34.4	34.1
Carcajou at Mackenzie	10KB1	3527	6500	50	3275	2552	127.5	64.8	+0.11	42.8	41.9	36.1	22.0
Arctic Red at Mackenzie	10LA1	8284	7500	100	3800	1148	131.7	65.4	+1.92	30.4	56.0	19.5	19.7
Loon at Mackenzie	10LB1	1168	950	50	500	694	128.6	67.0	-0.35	58.5	100.0	0.0	0.0
Tieda at Mackenzie	10LB2	365	1150	50	600	891	129.3	66.9	-0.48	63.1	100.0	0.0	0.0
Travaillant at Mackenzie	10LB3	1124	950	50	500	690	131.9	67.8	-0.40	55.9	100.0	0.0	0.0
Ontaratue at Mackenzie	10LB4	2646	500	100	300	457	131.0	66.6	-0.39	38.7	100.0	0.0	0.0
Rabbit Hay at Mackenzie	10LC1	139	950	50	500	382	132.8	67.4	+0.16	49.9	100.0	0.0	0.0
Pierre at Mackenzie	10LC2	259	850	25	438	307	133.0	67.5	-0.41	30.1	100.0	0.0	0.0
Rengleng at Mackenzie	10LC3	551	800	0	400	436	133.0	67.7	-0.21	50.3	100.0	0.0	0.0
Gull at Mackenzie	10LC4	662	325	0	163	454	133.5	68.3	-0.02	43.9	100.0	0.0	0.0
Hare Indian at Mackenzie	10LD1	4383	850	150	500	730	126.7	66.2	-0.35	40.9	100.0	0.0	0.0
Blue Fish at Hare Indian	10LD2	1580	1150	150	650	722	127.7	66.8	-0.51	58.6	100.0	0.0	0.0
Wind at Peel	10MA1	3783	5000	750	2875	3366	135.3	65.2	-0.11	47.8	24.0	41.2	32.5
Blackstone at Peel	10MA2	1512	6500	1250	3875	3747	138.0	65.1	-0.35	49.9	4.8	54.2	38.9
Ogilvie at Peel	10MA3	2791	5500	1250	3375	3114	138.9	65.3	-0.38	42.8	9.0	77.0	14.0
Hart at Peel	10MA4	4672	5250	1250	3250	3829	136.9	64.7	-0.34	51.5	5.8	50.0	42.1
Peel above Canyon Creek	10MA001	9709	5500	1011	3256	3404	137.7	65.0	-0.20	45.1	12.3	55.7	30.8
Snake at Peel	10MB1	2931	5500	450	2975	2858	133.2	65.6	-0.01	42.2	30.2	34.2	31.1
Bonnet Plume at Peel	10MB2	3724	6000	550	3275	3812	133.6	64.8	-0.10	37.6	17.8	35.6	40.1
Snake above Iron Creek	10MB001	1071	5500	1948	3724	4722	132.7	64.7	-0.42	54.1	1.3	23.0	63.2
Peel at Mackenzie Delta	10MC1	30404	5500	0	2750	2689	135.0	65.5	+0.58	39.7	37.0	40.2	21.0
Blow at Arctic Ocean	10MD1	1412	3500	0	1750	1320	137.5	68.6	-0.01	29.7	80.5	19.5	0.0
Babbage at Arctic Ocean	10MD2	1756	3500	0	1750	1272	139.1	68.9	+0.16	29.2	77.5	22.5	0.0
Firth at Arctic Ocean	10MD3	2425	4100	0	2050	2465	141.0	68.9	-0.37	43.6	30.0	65.0	5.0
Malcolm at Arctic Ocean	10MD4	427	5400	0	2700	2055	140.6	69.3	-0.06	34.6	47.2	44.7	8.1
Mountain at Mackenzie	10KC1	5785	5000	300	2650	4500	129.5	64.7	-0.41	57.2	11.0	27.7	48.3

Table 9 (cont'd.) Morphometric data

SUBBASINS		% AREA AT 6000 FT ELEVATION AND OVER	% AREA ABOVE AVERAGE ELEVATION	% LAKE AND SWAMP	% FOREST	% GLACIER	CIRCULATORY RATIO	ELONGATION RATIO	RELIEF RATIO X 100	WEIGHTED MEAN BIFURCATION RATIO	LENGTH RATIO	AREA RATIO	DRAINAGE DENSITY (Miles miles^{-2})
Redstone at Mackenzie	10HB001	21.9	56.0	1.1	48.1	0.4	0.567	0.615	0.89	4.18	1.80	3.72	0.885
Carcajou at Mackenzie	10KB1	0.0	43.3	1.6	54.8	0.0	0.413	0.611	1.04	4.07	2.00	4.91	0.852
Arctic Red at Mackenzie	10LA1	4.8	27.0	5.7	58.4	0.0	0.416	0.446	0.54	4.14	2.16	3.94	0.833
Loon at Mackenzie	10LB1	0.0	62.5	18.6	81.4	0.0	0.594	0.536	0.23	3.91	1.84	4.33	0.890
Tieda at Mackenzie	10LB2	0.0	75.8	14.9	85.1	0.0	0.640	0.617	0.59	4.31	1.95	4.20	0.887
Travaillant at Mackenzie	10LB3	0.0	61.8	25.6	74.4	0.0	0.528	0.620	0.28	4.38	2.29	4.85	0.900
Ontarate at Mackenzie	10LB4	0.0	14.6	13.3	86.2	0.0	0.534	0.775	0.39	4.28	2.17	4.61	0.694
Rabbit Hay at Mackenzie	10LC1	0.0	44.4	16.1	83.9	0.0	0.663	0.739	0.95	4.38	2.16	8.14	0.701
Pierre at Mackenzie	10LC2	0.0	5.4	31.7	68.3	0.0	0.741	0.790	0.66	4.00	1.69	7.75	0.712
Renglent at Mackenzie	10LC3	0.0	43.8	27.2	72.7	0.0	0.566	0.519	0.29	4.01	1.80	6.25	0.786
Gull at Mackenzie	10LC4	0.0	45.0	19.9	73.7	0.0	0.496	1.383	0.29	4.18	1.86	4.37	0.976
Hare Indian at Mackenzie	10LD1	0.0	26.0	13.5	86.1	0.0	0.525	0.733	0.13	4.09	2.06	4.22	0.790
Blue Fish at Hare Indian	10LD2	0.0	68.3	18.0	82.0	0.0	0.513	0.689	0.29	4.12	1.95	3.39	0.764
Wind at Peel	10MA1	2.3	46.2	2.5	40.8	0.0	0.463	0.609	0.70	4.07	2.20	5.69	0.985
Blackstone at Peel	10MA2	2.1	49.0	0.6	18.8	0.0	0.430	0.419	0.95	3.91	2.13	2.30	0.729
Ogilvie at Peel	10MA3	0.0	30.6	0.1	17.0	0.0	0.587	0.577	0.82	4.03	1.85	3.30	0.687
Hare at Peel	10MA4	2.1	51.7	0.5	24.1	0.0	0.588	0.585	0.57	4.36	2.24	4.48	0.678
Peel above Canyon Creek	10MA001	1.2	38.6	0.4	26.4	0.0	0.608	0.789	0.60	4.18	1.92	4.23	0.715
Snake at Peel	10MB1	4.5	39.0	1.1	56.6	0.1	0.277	0.466	0.73	4.23	2.28	2.94	1.047
Bonnet Plume at Peel	10MB2	6.5	46.2	1.6	30.1	0.2	0.240	0.394	0.57	4.26	2.34	2.53	0.851
Snake above Iron Creek	10MB001	12.5	57.8	0.1	5.1	0.2	0.383	0.507	0.92	4.49	2.19	7.24	0.792
Peel at Mackenzie Delta	10MC1	1.8	33.0	2.5	43.6	0.0	0.466	0.599	0.32	4.15	2.19	5.40	0.880
Blow at Arctic Ocean	10MD1	0.0	19.5	2.8	0.3	0.0	0.611	0.913	1.44	4.47	1.71	3.16	1.186
Babbage at Arctic Ocean	10MD2	0.0	22.5	4.9	0.0	0.0	0.618	0.774	1.07	4.72	1.82	3.52	1.014
Firth at Arctic Ocean	10MD3	0.0	48.8	3.3	1.3	0.0	0.473	0.483	0.67	4.56	2.02	5.56	0.841
Malcolm at Arctic Ocean	10MD4	0.0	28.0	0.2	0.0	0.0	0.486	0.511	2.18	5.25	1.94	14.93	0.953
Mountain at Mackenzie	10KC1	13.0	67.0	00.0	26.6	0.0	0.481	0.681	1.13	4.44	2.08	3.87	0.858

SUBBASINS		STREAM FREQUENCY	85-10 SLOPE FACTOR	CONSTANT OF CHANNEL MAINTENANCE (FT)	MAIN CHANNEL LENGTH (MILES)	DIRECT DISTANCE FROM MOUTH TO HEAD (MILES)	SINUOSITY RATIO	STREAM ORDER	PERIMETER (MILES)	HYDROLOGIC DATA	TOPOGRAPHIC MAP SCALE
Redstone at Mackenzie	10HB001	0.315	19.3	5966	196	143	1.37	7	594	YES	
Carcajou at Mackenzie	10KB1	0.426	1.9	6210	200	109	1.83	6	506	NO	
Arctic Red at Mackenzie	10LA1	0.428	10.5	6730	293	230	1.27	7	775	NO	
Loon at Mackenzie	10LB1	0.284	3.7	7293	107	72	1.49	6	204	NO	
Tieda at Mackenzie	10LB2	0.471	14.2	6984	48	35	1.37	5	106	NO	
Travaillant at Mackenzie	10LB3	0.327	5.9	7892	97	61	1.59	5	225	NO	
Ontaratue at Mackenzie	10LB4	0.128	3.1	12320	110	69	1.59	5	313	NO	
Rabbit Hay at Mackenzie	10LC1	0.223	23.5	8949	32	18	1.78	3	63	NO	
Pierre at Mackenzie	10LC2	0.212	12.3	10864	38	23	1.65	4	77	NO	
Rengleng at Mackenzie	10LC3	0.198	9.2	9231	78	51	1.53	4	147	NO	
Gull at Mackenzie	10LC4	0.437	3.9	5410	45	21	2.14	5	184	NO	
Hare Indian at Mackenzie	10LD1	0.263	3.3	7731	141	102	1.38	6	447	NO	
Blue Fish at Hare Indian	10LD2	0.249	4.4	8421	109	65	1.68	6	274	NO	
Wind at Peel	10MA1	0.519	18.7	5360	138	115	1.20	6	475	NO	
Blackstone at Peel	10MA2	0.304	18.1	7243	218	105	2.08	5	321	NO	
Ogilvie at Peel	10MA3	0.206	9.3	7686	158	104	1.52	6	321	NO	
Hare at Peel	10MA4	0.320	12.8	7788	184	132	1.39	6	412	NO	
Peel above Canyon Creek	10MA001	0.301	9.1	7385	197	142	1.39	7	578	YES	
Snake at Peel	10MB1	0.617	24.3	5043	168	131	1.28	6	691	NO	
Bonnet Plume at Peel	10MB2	0.506	17.8	6204	191	182	1.05	6	937	NO	
Snake above Iron Creek	10MB001	0.465	26.8	6667	81	73	1.11	6	216	YES	
Peel at Mackenzie Delta	10MC1	0.446	6.1	6000	448	327	1.37	7	1087	NO	
Blow at Arctic Ocean	10MD1	0.445	16.2	4452	76	46	1.65	6	216	NO	
Babbage at Arctic Ocean	10MD2	0.368	12.2	5207	121	62	1.95	6	244	NO	
Firth at Arctic Ocean	10MD3	0.296	20.5	6278	142	116	1.22	5	372	NO	
Malcolm at Arctic Ocean	10MD4	0.358	58.8	5540	56	47	1.19	4	155	NO	
Mountain at Mackenzie	10KC1	0.513	2.1	6160	210	126	1.67	7	559	NO	1: 250,000

Table 10. Computed Hydrologic Characteristics* of 26 Primary Watersheds (Multiple regression analysis).

		DA ($miles^2$)	MAF	T	MAFF	MAFH
1.	Root at Mackenzie	3835	1.24	4.00	11.22	12.14
2.	Willowlake River at Mackenzie	8179	0.81	5.21	9.70	10.59
3.	River between two mountains at Mackenzie	1345	0.71	7.84	9.17	9.67
4.	North Nahanni at Mackenzie	2751	1.50	6.00	12.35	13.31
5.	Keele at Mackenzie	10467	1.07	6.62	12.29	13.44
6.	Dahadinni at Mackenzie	1046	0.91	8.16	12.71	13.72
7.	Johnson at Mackenzie	855	0.55	3.95	9.80	10.71
8.	Wrigley at Mackenzie	502	0.82	8.59	12.77	13.80
9.	Redstone at Mackenzie	6080	1.89	6.69	14.19	15.07
10.	Carcajou at Mackenzie	3527	1.07	4.38	11.17	12.71
11.	Arctic Red at Mackenzie	8284	0.90	12.39	12.70	13.66
12.	Mountain at Mackenzie	5785	1.66	8.04	12.58	13.45
13.	Loon at Mackenzie	1168	0.57	8.02	9.19	12.91
14.	Tieda at Mackenzie	365	0.46	7.47	11.16	12.86
15.	Travaillant at Mackenzie	1124	0.15	6.98	12.60	13.72
16.	Ontaratue at Mackenzie	2646	0.30	7.54	10.06	10.60
17.	Rabbit Hay at Mackenzie	139	0.12	2.58	10.87	11.61
18.	Pierre at Mackenzie	259	0.55	7.84	12.58	12.79
19.	Rengleng at Mackenzie	551	0.50	6.43	13.28	13.37
20.	Gull at Mackenzie	662	0.46	5.47	18.81	20.35
21.	Hare Indian at Mackenzie	1383	0.60	7.50	10.12	10.76
22.	Peel at Mackenzie (Delta)	30404	0.93	6.31	15.03	16.26
23.	Blow at Arctic Ocean	1412	0.87	4.33	18.18	20.26
24.	Babbage at Arctic Ocean	1756	0.78	3.24	14.97	16.58
25.	Firth at Arctic Ocean	2425	0.95	5.72	11.09	12.26
26.	Malcolm at Arctic Ocean	427	0.78	9.12	12.54	13.91

* All runoff values are presented in cubic feet per second per square mile.

Table 11. Estimated Hydrologic Characteristics* of 14 Gauged Watersheds (Flood Frequency Analysis)

STATION NUMBER	MAF	T	MAFF	MAFH	BASIN AREA MILES^2
10AA001	1.07	4.91	8.59	9.32	13675
10AB001	1.25	4.71	9.85	11.01	4952
10AC002	1.52	8.03	13.14	14.11	2710
10AC004	1.08	5.03	7.76	8.24	682
10AD001	1.60	6.54	12.41	13.67	3424
10BA001	1.34	4.88	9.92	11.06	2519
10BB001	1.06	4.36	7.25	7.76	8533
10BB002	1.25	4.47	6.50	6.86	4249
10BC001	0.99	5.80	11.88	13.20	3620
10EA003	1.06	6.19	11.72	12.88	3326
10EB001	2.05	7.93	13.97	15.14	5653
10HB001	1.13	--	--	--	6080
10MA001	0.91	--	--	--	9709
10MB001	3.92	--	--	--	1071

* All runoff values are presented in cubic feet per second per square mile.

Table 12. Comparison of Computed (Multiple Regression) and Estimated (Flood frequency) Hydrologic Characteristics* of 14 Gauged Watersheds

WATERSHED	DA ($miles^2$)	MAF		T		MAFF		MAFH	
		Est.	Compt.	Est.	Compt.	Est.	Compt.	Est.	Compt
10AB001	4952	1.25	1.30	4.71	4.87	9.85	10.72	11.01	11.7
10AA001	13675	1.07	1.33	4.91	5.12	8.60	12.85	9.33	13.8
10AC002	2710	1.52	1.51	8.03	7.89	13.14	12.50	14.11	13.4
10AC004	682	1.08	1.06	5.03	5.81	7.76	9.74	8.24	10.5
10AD001	3424	1.60	1.57	6.54	6.31	12.41	14.42	13.67	15.8
10BA001	2519	1.34	1.28	4.86	4.88	9.92	8.61	11.06	9.4
10BB002	4249	1.25	1.62	4.47	5.97	6.50	8.77	6.86	9.1
10BB001	8533	1.06	1.67	4.36	5.70	7.25	8.97	7.76	9.4
10BC001	3620	0.99	1.05	5.80	5.49	11.88	11.84	13.20	13.2
10EA003	3326	1.06	1.06	6.19	5.97	11.72	11.80	12.88	12.9
10EB001	5653	2.05	1.97	7.93	7.56	13.97	12.72	15.14	13.7
10HB001	6080	1.13	1.89						
10MA001	9709	0.91	0.79						
10MB001	1071	3.92	1.28						

* All runoff values are presented in cubic feet per second per square mile.

Table 13. Computed Hydrologic Characteristics* of all Watersheds under Study (Multiple-regression analysis)

	WATERSHED	NO.	AREA (MILES)^2	MAF	T	MAFF	MAFH
1.	Liard above Meister	10AA1	3639	1.21	5.21	14.28	15.90
2.	Meister at Liard	10AA2	805	1.01	3.02	9.62	10.41
3.	Rancheria at Liard	10AA3	2021	1.40	4.69	12.08	12.97
4.	Francis near Watson Lake	10AB001	4952	1.30	4.87	10.72	11.73
5.	Liard at Upper Crossing	10AA001	13675	(5)1.33	5.12	12.85	13.87
6.	Dease at McDame	10AC002	2710	1.51	7.89	12.50	13.43
7.	Blue at Dease	10AC004	682	1.06	5.81	9.74	10.57
8.	Dease at Liard	10AC3	5754	1.42	7.10	8.86	9.46
9.	Hyland near Lower Post	10AD001	3424	1.57	6.31	14.42	15.80
10.	Turnagain at Kechika	10BA1	2696	1.20	5.60	8.25	8.93
11.	Turnagain Gauging Station	10BA001	2519	1.28	4.88	8.61	9.41
12.	Kechika above Boya Creek	10BA002	4249	1.62	5.97	8.77	9.19
13.	Kechika at Liard	10BB001	8533	1.67	5.70	8.97	9.49
14.	Coal at Liard	10BC001	3620	1.05	5.49	11.84	13.27
15.	Beaver at Liard	10BD1	4184	1.34	7.63	9.25	9.83
16.	Flat at S. Nahanni	10EA003	3326	1.06	5.97	11.80	12.90
17.	S. Nahanni above Virginia Falls	10EB001	5653	1.97	7.56	12.72	13.75
18.	Root at Mackenzie	10GA1	8179	1.24	4.00	11.22	12.14
19.	Willowlake River at Mackenzie (E)	10GB2	1345	0.81	5.21	(7)9.70	(8)10.59
20.	River Between Two Mountains at Mackenzie (E)	10GB1	2751	0.71	7.84	(7)9.17	(8) 9.67
21.	N. Nahanni at Mackenzie	10GD1	1149	1.50	6.00	12.35	13.31
22.	Ram at N. Nahanni	10GD2	1509	1.21	7.99	15.27	16.74
23.	Tetcela at N. Nahanni	10GD3	10467	0.57	(6)4.48	10.47	11.37
24.	Keele at Mackenzie	10HA1	1046	(5)1.07	6.62	12.29	13.44
25.	Dahadinni at Mackenzie	10HB1	855	0.91	8.16	12.71	13.72
26.	Johnson at Mackenzie	10HB2	502	0.55	3.95	9.80	10.71
27.	Wrigley at Mackenzie	10HB3	6080	0.82	8.59	12.77	13.80
28.	Redstone at Mackenzie	10HB001	3527	1.89	6.69	14.19	15.07
29.	Carcajou at Mackenzie	10KB1	8284	1.07	4.38	11.71	12.71
30.	Arctic Red at Mackenzie	10LA1	1168	0.90	(6)12.39	12.70	13.66
31.	Loon at Mackenzie (E)	10LB1	365	0.57	8.02	9.19	12.91
32.	Tieda at Mackenzie (E)	10LB2	1124	0.46	7.47	11.16	12.86
33.	Travaillant at Mackenzie (E)	10LB3	2646	0.15	6.98	12.60	13.74
34.	Ontaratue at Mackenzie	10LB4	139	0.30	7.54	10.06	10.60
35.	Rabbit Hay at Mackenzie (E)	10LC1	259	0.12	2.58	10.87	11.61
36.	Pierre at Mackenzie (E)	10LC2	551	0.55	7.84	12.58	12.79
37.	Rengleng at Mackenzie (E)	10LC3	662	0.50	6.43	13.28	13.37
38.	Gull at Mackenzie (E)	10LC4	1383	0.46	5.47	18.81	20.35
39.	Hare Indian at Mackenzie (E)	10LD1	1580	0.60	7.50	10.12	10.76
40.	Blue Fish at Hare Indian (E)	10LD2	3783	0.50	8.85	11.34	11.99
41.	Wind at Peel	10MA1	1512	1.11	3.52	16.31	17.97
42.	Blackstone at Peel	10MA2	2791	1.12	5.57	(7) 8.21	(8) 9.00
43.	Ogilvie at Peel	10MA3	4672	1.31	7.56	(7)10.56	(8)11.34
44.	Hart at Peel	10MA4	9707	1.26	5.84	(7) 7.84	(8) 8.61
45.	Peel above Canyon Creek	10MA001	2931	(5)0.76	6.05	16.20	17.31

Table 13 (Cont'd.) Computed Hydrologic Characteristics* of all Watersheds under Study (multiple-regression analysis

	WATERSHEDS	NO.	AREA $(MILES)^2$	MAF	T	MAFF	MAFH
46.	Snake at Peel	10MB1	2931	0.84	1.90	15.30	17.01
47.	Bonnet Plume at Peel	10MB2	3724	1.09	3.19	11.93	13.09
48.	Snake above Iron Creek	10MB001	1071	1.28	4.91	11.94	12.94
49.	Peel at Mackenzie Delta	10MC1	30404	(5)0.93	6.31	(7)15.03	(8)16.26
50.	Blow at Arctic Ocean	10MD1	1412	0.87	4.33	(7)18.18	(8)20.26
51.	Babbage at Arctic Ocean	10MD2	1756	0.78	3.24	(7)14.97	(8)16.58
52.	Firth at Arctic Ocean	10MD3	2425	0.95	5.72	(7)11.09	(8)12.26
53.	Malcolm at Arctic Ocean	10MD4	427	0.78	9.12	12.54	13.91
54.	Mountain at Mackenzie	10KC1	5785	1.66	8.04	12.58	13.45

(E) Indicates basins east of Mackenzie River.
(5), (6), (7), (8) These values have been estimated from equations (5), (6) (7) and (8) respectively.
* All runoff values are presented in cubic feet per second per square mile.

SUSPENDED SEDIMENT AND DISSOLVED MATERIAL TRANSPORT IN "TWISTY CREEK", A Small Subarctic Watershed

by

J.N. Jasper

Technical Report 15 to
Glaciology Division
Water Resources Branch
Department of the Environment

under the

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Northern Pipelines

ABSTRACT

Data are presented for suspended sediment and dissolved material transport in a small subarctic watershed. Variation of sediment concentrations and yield with discharge is analyzed and total sediment loss from the watershed estimated. Temporal and spatial variation in water chemistry is examined in an attempt to determine source area for runoff. Estimates of basin hydrologic characteristics are obtained utilizing hydrochemistry data.

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SUSPENDED SEDIMENT AND DISSOLVED MATERIAL TRANSPORT IN "TWISTY CREEK", A SMALL SUBARCTIC WATERSHED

by

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1. INTRODUCTION

The proposed construction of pipeline and highway routes through the Mackenzie Valley has revealed a general lack of data and knowledge of precipitation, runoff and erosion patterns for much of the area. The present watershed study presents data and attempts to quantify the relationships between these processes, and may be of some use in determining construction guidelines for structures in drainage basins subject to similar physiographic and precipitation characteristics.

The data presented in this paper are for dissolved material and suspended sediment load during the period July 2 to August 11, 1972 and reflect the pattern and importance of running water in the erosion and transportation of sediment.

2. CHARACTERISTICS OF THE STUDY WATERSHED

The results comprise part of the preliminary study of hydrologic and fluvial processes on "Twisty Creek", a small subtributary of the Arctic Red River. The watershed is located in the foothills of the Mackenzie Mountains, N.W.T., at latitude 65° 23' N and longitude 131° 16' W (Figure 1), and has a drainage area of 6.55 km^2 above the main stream gauging site.

The physiography of the watershed is characterized by narrow V-shaped valleys, steep talus-covered slopes and occasional rock outcrops at higher elevations. Lower down, the stream flows over a narrow floodplain and into a narrow vertical-walled canyon. The stream flows in this canyon, except for a short distance near the main stream gauging site, until released upon a wide floodplain below the secondary stream gauging site (Figure 2).

Bedrock outcrops in the watershed are dominantly limestones and dolomites of the Devonian era, with minor occurrence of interbedded shales and sandstones and the remnants of pebble conglomerates also present. Most slopes are overlain by highly weathered scree and floodplain deposits consist of well-rounded cobbles and boulders.

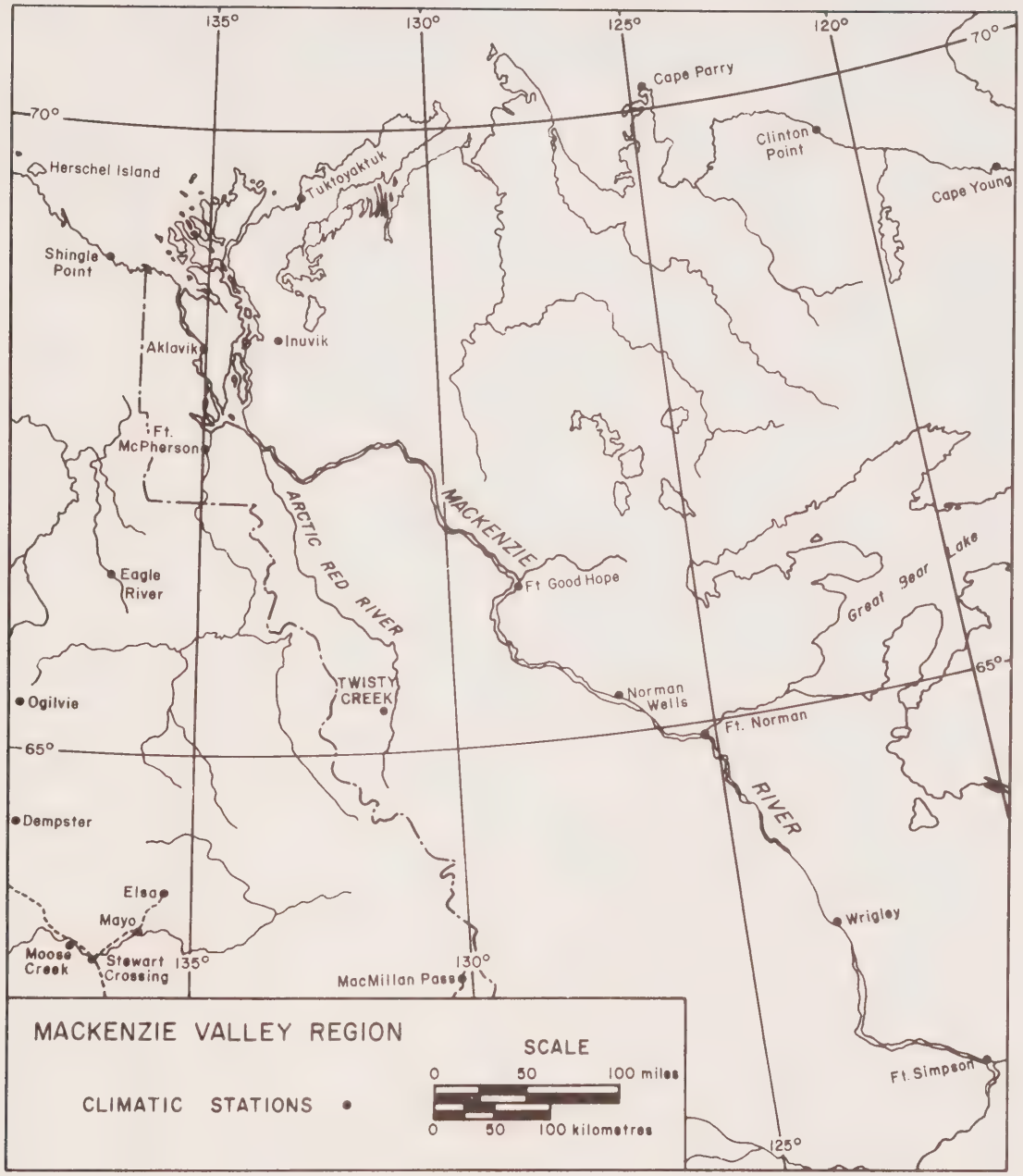


Figure 1. Mackenzie Valley region showing the location of the research watershed and climatic stations.

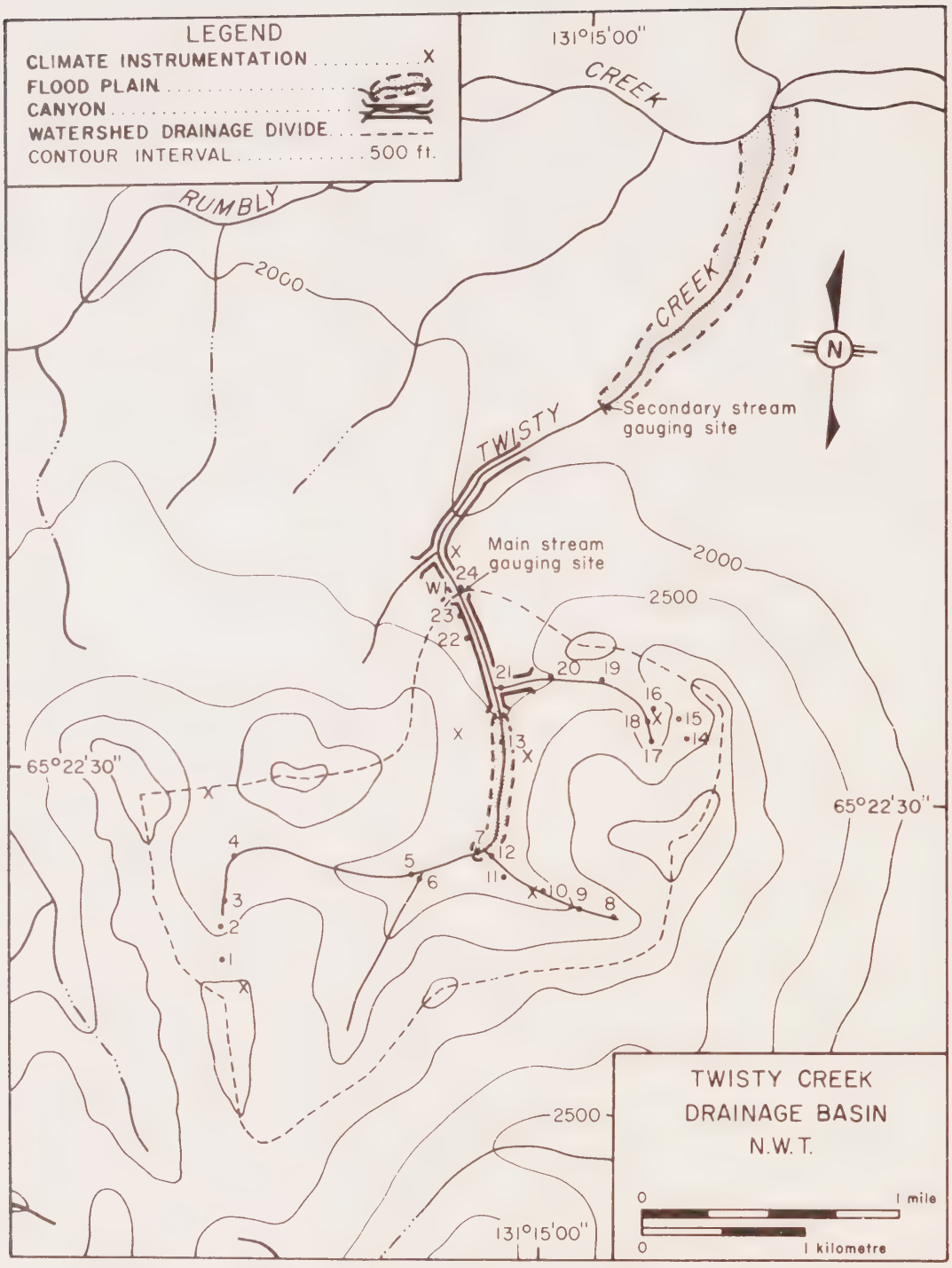


Figure 2. "Twisty Creek" drainage basin; numbers refer to sites identified in Table 2.

Above the 900 m level, vegetation is limited to isolated patches of mosses and grass. Grass becomes dominant on slopes near the main stream channel in the upper part of the watershed. Isolated growths of small stunted spruce are present along the main channel near the edge of the mountains and increase in size and density towards the mouth of the watershed.

3. METHODS OF DATA COLLECTION

3.1 Climate and Runoff

Six tipping bucket rain gauges and three hygrothermographs were utilized to record rainfall intensity, air temperature and humidity in the basin during the field season. Also, an automatic weather station located three miles from the basin has recorded air temperature and humidity, ground temperature, wind speed and direction, barometric pressure, relative humidity and solar radiation at three-hour intervals since its installation in August, 1971.

A continuous record of stream stage was kept using Stevens stage recorders at two stilling well installations. Velocity was measured with an Ott current meter and a rating curve for the main stream gauging site developed from 12 such measurements. A more detailed discussion of climate and runoff may be obtained by reference to a companion report on this aspect of the study by Sellars (1972).

3.2 Suspended and Dissolved Load

Stream borne material is usually considered to fall into three categories: bed load, suspended load and dissolved load. The term "bed load" applies to sediment that moves by sliding, rolling and the process of saltation. No data on bed load and suspended load close to the bed were collected as their measurement is extremely difficult during peak flow conditions.

A U.S. DH-48 suspended sediment sampler was used to collect samples for the determination of suspended sediment concentrations at the main stream-gauging site. The instrument consists of a nozzle designed to admit flowing water and suspended material in the proportions in which they are present in the stream, and a removeable bottle to collect the sample. The sampler, with rod attachments for holding and positioning the sampler in the flow, is lowered in the flow at a constant rate until the bottom is reached, then immediately raised at the same rate to obtain a depth-integrated sample of suspended sediment for the column of water samples. When the sampler touches bottom, the nozzle is still 9 cm above the bed. Therefore, sediment travelling close to the bed is not sampled.

For each determination, one sample was taken at the centre of the stream and filtered through 0.45 micron millipore filters. The volume of samples was recorded and the filter papers were stored for later analysis by the Sediment Survey Laboratory of the Water Survey of Canada. Samples taken at discharges exceeding $3m^3$/sec during the peak flood in the watershed were too turbid to be filtered and required shipment of samples to the laboratory, where standard procedures were utilized to determine suspended sediment concentration.

Estimates of dissolved material are based on the results of 221 water samples, which were obtained from sites within the catchment and analyzed for pH, calcium and total hardness and alkalinity. The pH determinations were made with a Delta 260A Photometric Analyzer. Calcium and total hardness were obtained through EDTA titration methods (Traversy, 1971), giving concentrations as $CaCO_3$ in parts per million to an accuracy of ±1 parts per million. Titration of samples to a pH of 4.5 with sulphuric acid gave alkalinity to an accuracy of ±5 parts per million as $CaCO_3$.

The samples were collected in the sample bottles used for suspended sediment and sealed with a paper cover and an air-tight plastic cap. Most of the analyses were completed within four hours of sample collection and all within fifteen hours. Repeated testing over a similar lapse of time indicated that capping of sample bottles maintained the original chemical properties, except pH. As the latter tended to decrease slightly, determination of pH was carried out as soon as possible after sampling. The locations of a number of frequently sampled sites within the basin are shown in Figure 2.

3.3 Data Analysis

A discharge-suspended sediment concentration relationship was developed for the watershed at the main gauging site based on the stage-discharge curve for the section and 33 suspended sediment samples. The sediment samples were collected throughout the field season over a range in discharge of 0.1 to 9.0 m^3/sec. The concentrations of sediment (in gm/l) are plotted against discharge in Figure 4 and the following regression equations were obtained:

$$SSC = 0.058\ Q^{2.11}, \quad Q \geq 0.4\ m^3/sec$$

$$SSC = 0.01\ Q, \quad Q < 0.4\ m^3/sec$$

where SSC is the suspended sediment concentration in gm/l and Q is a stream discharge.

Discharge-dissolved load rating curves were developed in a similar manner from 138 water chemistry analyses carried out at the main stream gauging site. Although the initial plot of dissolved load and discharge produced a wide scatter of points, closer exam-

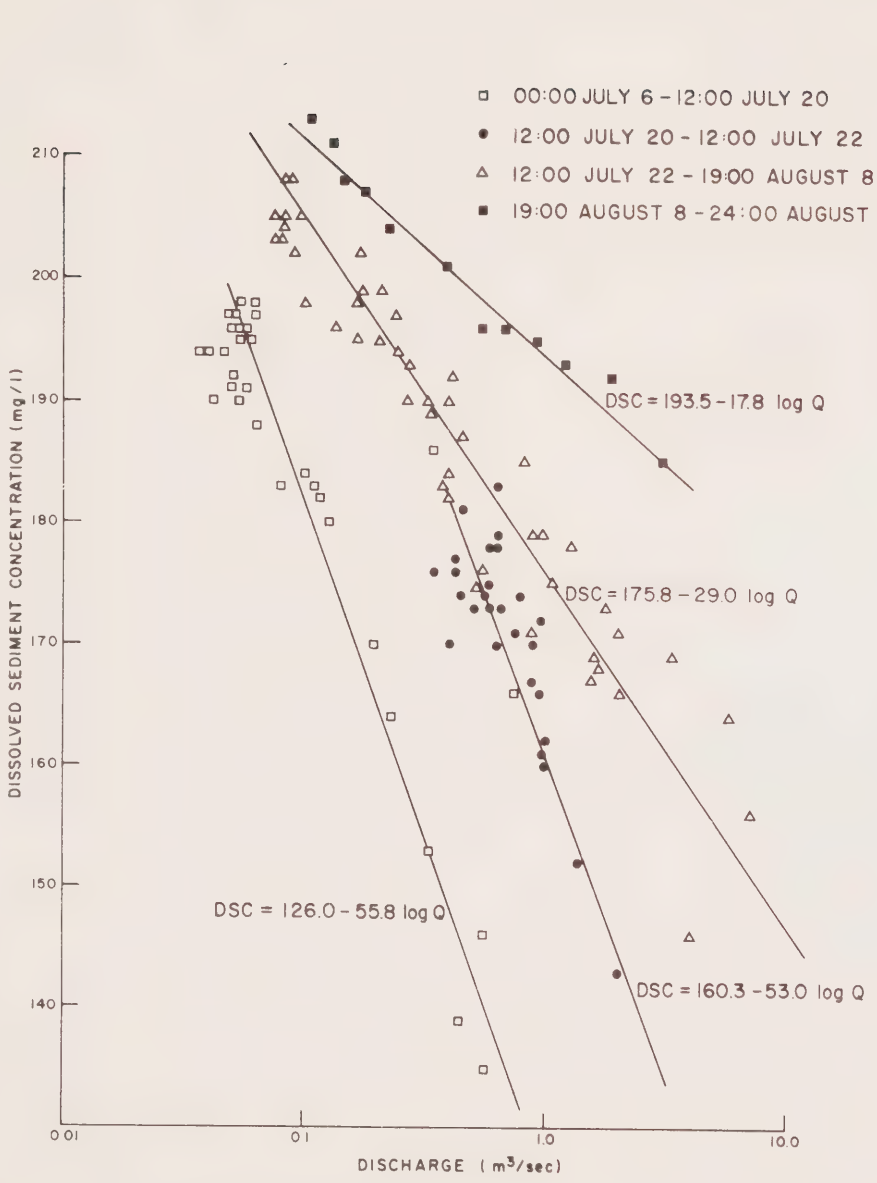


Figure 3. Dissolved load rating curves.

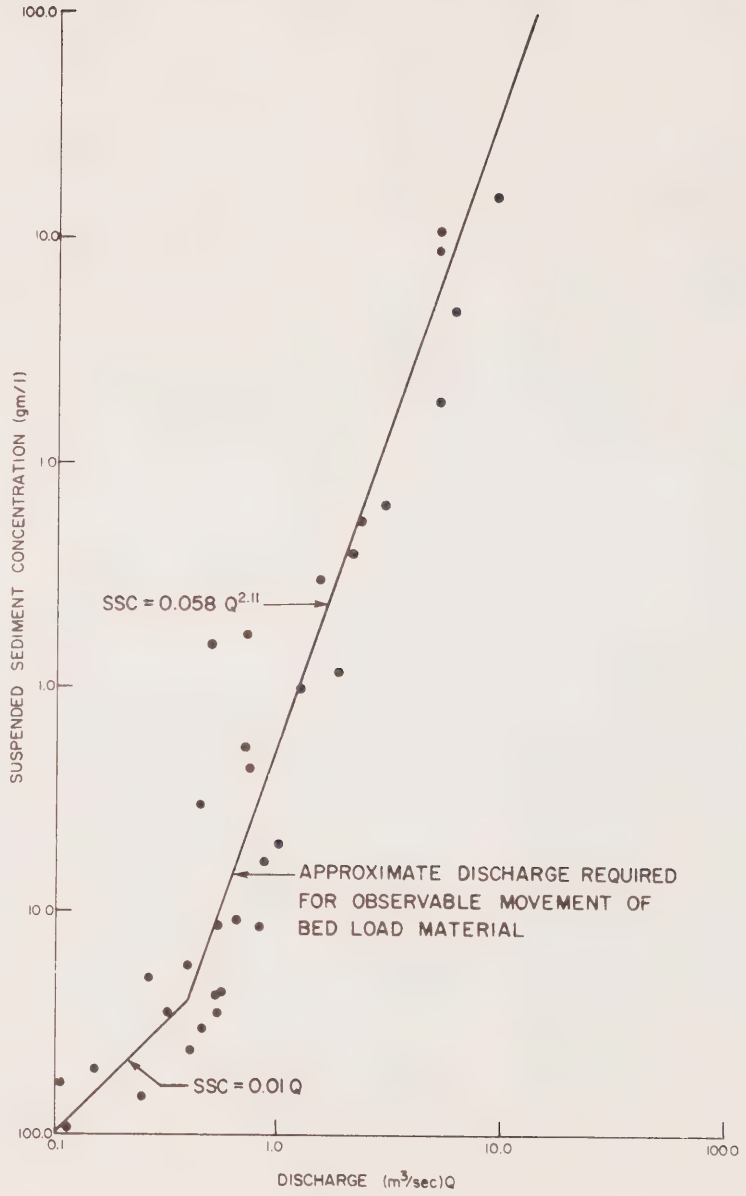


Figure 4. Suspended sediment rating curve.

ination of the change of dissolved material concentrations over the field season suggested that distinct relationships existed for various periods of time. The data are plotted in Figure 3 and the following regression lines fitted by eye:

DSC = 126.0 - 55.8 log Q, 00:00 h July 6 to 12:00 h July 20

DSC = 160.3 - 53.0 log Q, 12:00 h July 20 to 12:00 h July 22

DSC = 175.8 - 29.0 log Q, 12:00 h July 22 to 19:00 h August 8

DSC = 193.5 - 17.8 log Q, 19:00 h August 8 to 24:00 h August 11

where DSC is the dissolved load concentration in mg/l and equals the sum of total hardness and alkalinity concentrations.

Comparison of dissolved load and discharge (Figure 5) indicated that transition from one rating curve to another coincides with the major floods in the watershed. The phenomenon is attributed to changes in the relative contribution of groundwater flow to runoff. For precipitation events of long duration, groundwater flow has a longer period in which to approach equilibrium with rainfall rate; therefore, the proportion of groundwater at equivalent discharges to short "flashy" floods is greater and higher dissolved material concentrations in total streamflow result.

It is also proposed that evaporation of stream waters causes dissolved material to precipitate out of the water onto the stream banks, later to be redissolved by flood waters and increase the concentration of dissolved materials. If individual floods did not entirely remove these precipitates, then the deposits would tend to increase during the summer and result in highest dissolved sediment concentrations late in the field season.

4. RESULTS AND DISCUSSION

4.1 Sediment Transport

Although bed load was not measured, simple qualitative observations were made at the main stream gauging site. Examination of the section before and after floods showed that movement of bed material did not occur in observable quantities for discharges less than 1.0 m^3/sec. Evidence is provided by the lack of accumulation of bed material in deep pools along the stream course for floods with peak discharges between 0.80 and 1.0 m^3/sec. Discharges in excess of 1.0 m^3/sec resulted in the deposition of material ranging in size from coarse sand to small pebbles and stones in these pools, and caused minor problems in the intake system of the water level recorder.

During the flood of August 8, major bank erosion occurred at several points along the main channel. As the peak discharge

of 9.15 m^3/sec was approached, large boulders could be heard bouncing along the bed. Post-flood examination of the channel revealed accumulations of as much as 2 feet of cobbles and boulders at some points along the channel.

Streamflow and dissolved and suspended load were obtained from a computer program, which integrated the continuous stage records over time and produced daily and peak totals given in Table 1. These data illustrate the overwhelming effect of the storm of August 8 on basin sediment yield.

At the peak discharge of 9.15 m^3/sec, suspended sediment was passing the gauging station at a rate of 56.6 kg/sec (about 125 lbs/sec). This value is 81 times larger than the second largest maximum suspended transport rate of 0.70 kg/sec for discharges of 2.23 m^3/sec on July 20 and 22. The 12 hour period from 19:00 August 8 to 7:00 August 9, comprised about 2.5% of the total period of record and produced over 93% of the total suspended sediment yield of 427,000 kg (about 420 tons).

The range in daily and peak rates of dissolved load is much less than that for suspended sediment, as dissolved material concentrations tend to decrease sharply with increases in discharge. The net effect of increased runoff, however, is to produce an increase in total transport. Thus, the maximum rate of 16.1 gm/sec on August 8 is only 4 to 6 times larger than rates of dissolved sediment yield for storms on July 20 and 22, and August 2.

Dissolved load concentrations were calculated from water chemistry data as the sum of total hardness and alkalinity, and therefore, do not include the minerals undetected by the tests. A more complete analysis of a single sample from the area indicates that the main component missed was sulphate, as would be expected from the limestone and dolomite bedrock. The ion balance for all samples was calculated using a computer program developed by T. Wigley of the University of Waterloo, (Wigley, 1971) and indicated that 75 to 80% of the total dissolved load had been monitored.

Correction for this underestimation of total dissolved material transport would raise the yield for the field season from 1,640 kg to about 2,100 kg (1.8 to 2.3 tons respectively). Despite the adjustment, dissolved load transport remains of minor erosional significance.

4.2 Temporal and Spatial Variations in Water Chemistry

The pH, calcium and magnesium hardness and alkalinity values of water samples from a number of sites in "Twisty Creek" are listed in Table 2. Site locations are shown on Figure 2. Several samples were collected at each site to investigate the consistency of spatial differences during the field season.

TABLE 1: DAILY DISSOLVED AND SUSPENDED LOAD YIELD

Date	Mean Discharge (m^3/sec)	Peak Discharge (m^3/sec)	Daily Total Suspended (kg)	Daily Total Dissolved (kg)	Daily Peak Suspended (kg/sec)	Daily Peak Dissolved (gm/sec)
July 2	0.10	0.13	8.11	15.10		
3	0.09		7.00	14.20		
4	0.06		3.34	10.40		
5	0.05		2.10	8.47		
6	0.05		1.93	8.15		
7	0.06		2.70	9.41		
8	0.05		2.40	8.96		
9	0.04		1.53	7.35		
10	0.04		1.27	6.79		
11	0.04		1.27	6.79		
12	0.04		1.22	6.67		
13	0.04		1.27	6.79		
14	0.04		1.20	6.61		
15	0.04		1.18	6.40		
16	0.05		2.07	8.57		
17	0.05		2.13	8.51		
18	0.12	0.81	83.42	16.40	0.03	1.06
19	0.12		16.92	18.40		
20	0.61	*2.23	4,500.00	78.10	0.70	2.38
21	0.52	*1.04	875.00	77.60	0.07	1.65
22	1.12	*2.23	12,300.00	164.00	0.70	3.70
23	0.55	0.60	965.00	87.40	0.01	1.34
24	0.39		284.00	62.30		
25	0.10		30.20	31.50		
26	0.12		12.10	20.60		
27	0.89		6.72	15.10		
28	0.12	0.39	18.30	19.80		
29	0.24		52.90	39.60		
30	0.12		13.40	21.10		
31	0.09		7.08	16.40		
Aug. 1	0.26		353.00	42.60		
2	0.74	*1.70	3,790.00	114.00	0.30	2.87
3	0.47		758.00	74.40	0.03	1.51
4	0.20		34.30	33.10		
5	0.12		12.50	21.40		
6	0.10		9.58	17.40		
7	0.39	0.88	466.00	62.80	0.04	1.56
8	1.19	*9.15	328,000.00	184.00	56.60	16.10
9	1.32		73,900.00	215.00		
10	0.24		55.20	43.00		
11	0.14		17.20	24.80		
TOTAL	0.25		427,000.00	1,640.00		

* movement of bed material observed.

TABLE 2 WATER CHEMISTRY OF "TWISTY CREEK"

(pH/calcium hardness/magnesium hardness/alkalinity)

Site No.	Description	6 July	9 July	19 July	20 July	27 July	29 July	7 August
1	Rock outcrop seepings				8.69/56/12/62			
2	Pit in talus filled rill				8.74/56/20/70			
3	Stream, 200 m downstream				8.74/56/19/70			
4	Stream, 300 m further				8.70/58/22/75			
5	Stream at mouth	8.35/59/27/90			8.48/63/25/75	8.73/70/27/93		9.16/68/26/87
6	Stream at mouth	8.51/50/26/75			8.65/52/24/70	8.87/58/28/80		
7	Twisty Creek above Lower Forks	8.55/59/29/102		8.85/57/27/80		8.88/68/27/90	8.85/63/27/87	8.86/66/26/85
								8.86/56/26/74*
8	Pit in talus filled rill			8.61/58/20/78				
9	Stream, 200 m downstream			8.63/58/23/78				
10	Stream, 200 m further			8.80/68/23/85				
11	Mouth at large steep rill							8.35/34/17/50*
12	Stream at mouth	8.75/63/25/95		8.88/68/22/85	8.70/64/24/85	8.89/78/23/88	8.87/73/20/88	8.84/71/23/86
								8.73/49/17/61*
13	Twisty Creek resurgence, main channel dried up	8.70/66/27/90				8.85/77/20/93		
14	Snowmelt, pit in snowbank		8.35/32/12/48					
15	Snowmelt, at base of snowbank		8.30/21/13/35					
16	Stream at mouth		8.65/49/22/72	8.80/60/25/80			8.86/71/25/44	
17	Pit in talus filled rill		8.80/58/20/80					
18	Stream at mouth		8.85/58/24/80	8.85/59/24/85			8.84/76/12/80	
19	Stream, 200 m further		8.60/66/24/85	8.78/64/24/85				
20	Stream at waterfall		8.80/94/24/120				8.80/78/19/95	9.01/68/22/82*
21	Stream at mouth					8.80/103/32/128		
22	Small stream, 100 m from spring						8.80/102/31/126	
23	Small spring						8.80/101/41/137	
24	Twisty Creek at gauging site	8.78/69/28/100	8.89/68/28/98	8.86/64/29/90	8.54/68/22/80	8.86/77/28/98	8.92/73/28/98	8.88/73/27/87
								8.70/60/26/75*

* Analysis of flood stage waters

Low pH seems to be associated with low hardness and alkalinity and snowmelt early in the field season (sites 5-7 on July 6, sites 14-16 on July 9) while values of pH tend to be higher with increased hardness and alkalinity in the latter part of the field season.

The highest values of calcium and magnesium were recorded at site 20 on July 9, site 21 on July 27 and sites 22 and 23 on July 29. On July 9 and 27, discharge in the stream was very low and the stream flowed underground at several places. The July 29 samples are from spring-fed streams and are thought to be representative of deeply circulating groundwater flow.

Hardness is low at the stream "source" and increases as the water travels downslope and dissolves material. However, as slope surfaces are covered by talus, downslope flow for considerable distances is through this material. Thus calcium and magnesium hardness commonly achieve concentrations of 50 and 20 mg/l, respectively, before flow appears on the surface and can be sampled.

Alkalinity shows a similar pattern to hardness, with high concentrations found in essentially groundwater flows at sites 20-23 on the dates noted, and low values associated with snowmelt and rising stages of the main stream.

The variation of hydrochemistry at the main stream gauging site on "Twisty Creek" is given in Figure 5. Alkalinity, calcium and magnesium hardness seem fairly steady over the early part of the field season, when little precipitation fell, as discharge was due to baseflow. A diurnal variation in pH is evident, with a similar, but less pronounced pattern exhibited by alkalinity, calcium and magnesium. A period of heavy precipitation lasting from late July until mid August caused an initial decrease in alkalinity and calcium hardness, followed by a systematic, but somewhat erratic increase over the rest of the summer. This latter trend is thought to be the result of increasing contribution from groundwater, made possible by circulation of water through the limestone and dolomite of the basin. Values of pH measured at the site indicate an upward trend from 8.70 to 9.00 during the period, while magnesium hardness decreased marginally.

4.3 Hydrochemistry of "Twisty Creek"

The consideration of changes in the hydrochemistry of the watershed during the floods of July 18-19 and August 6-11, in conjunction with data in Table 2, is quite useful in developing a hypothesis of the relationship between climate, geology, water chemistry and the various components contributin to runoff.

For example, the flood on July 18 resulted from a short duration, high intensity thunderstorm that ended the lengthy warm

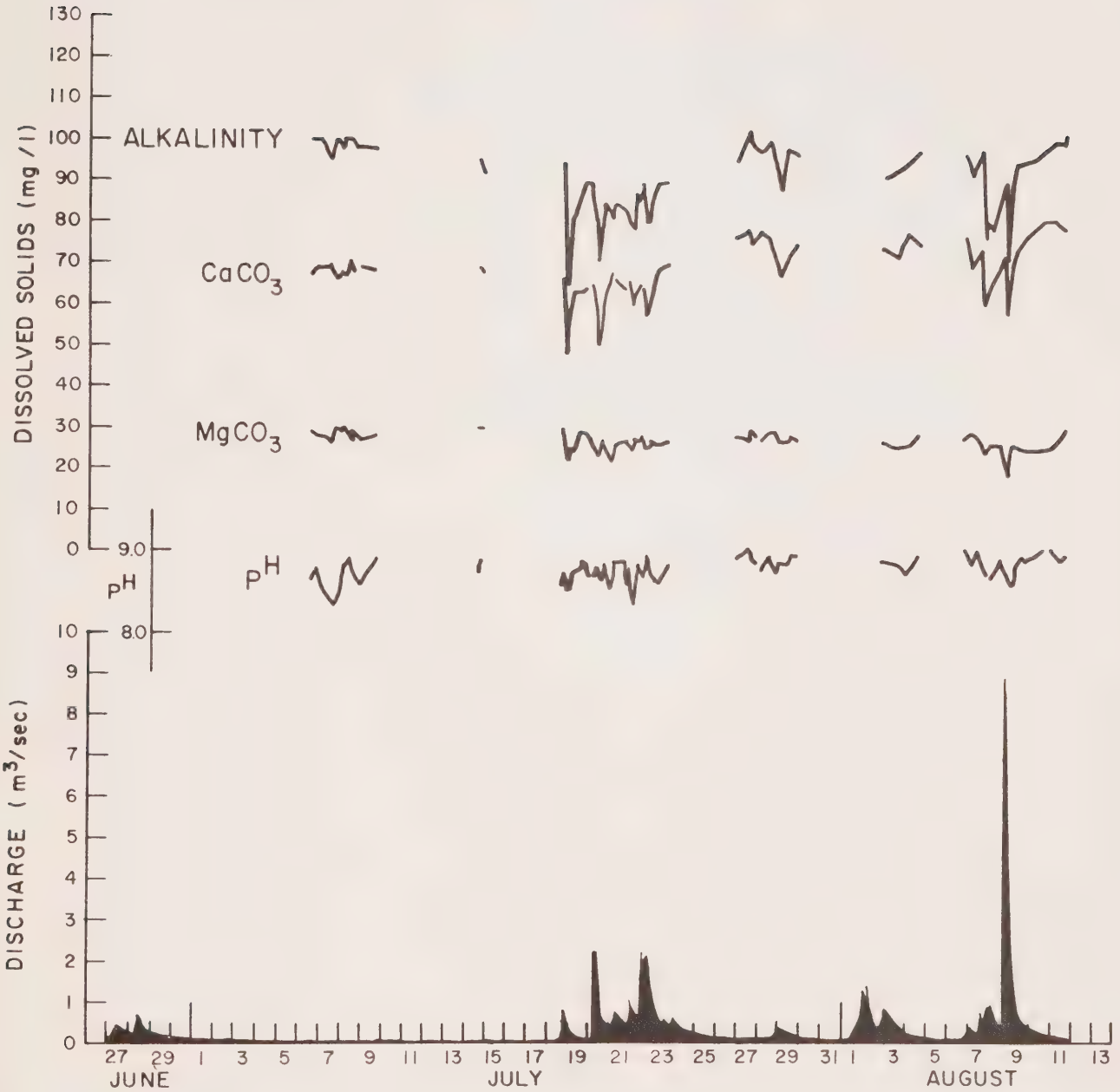


Figure 5. "Twisty Creek" hydrochemistry, 1972.

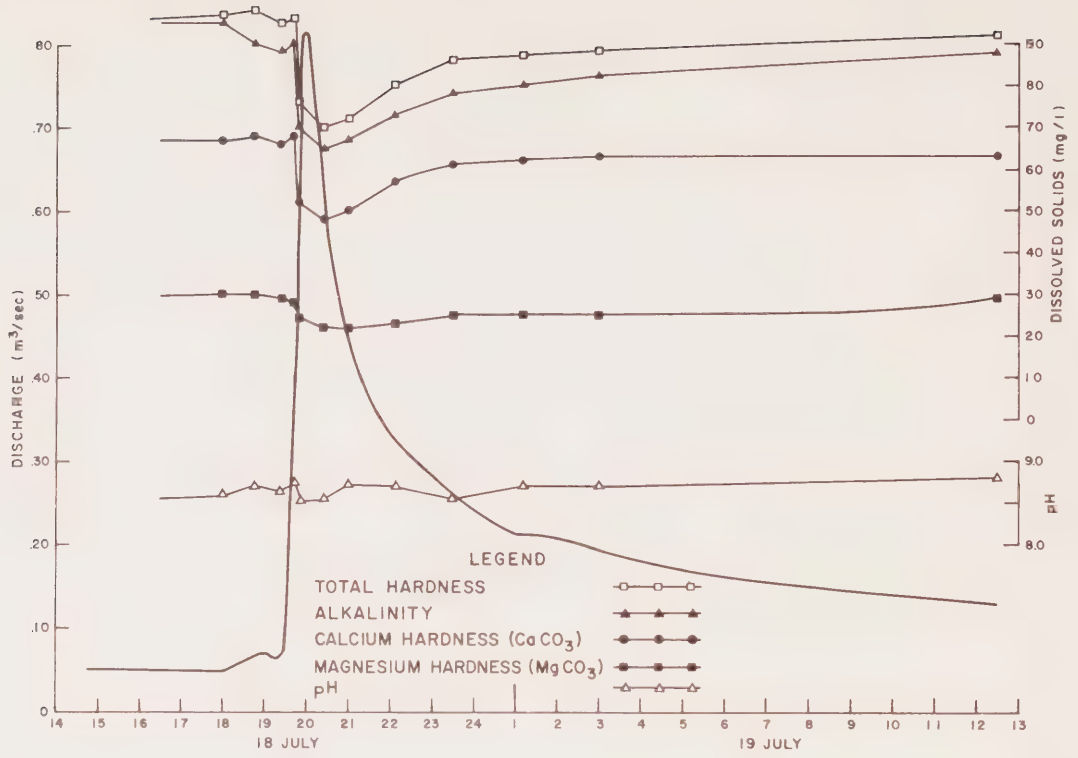


Figure 6. "Twisty Creek" flood hydrochemistry - July 18-19, 1972.

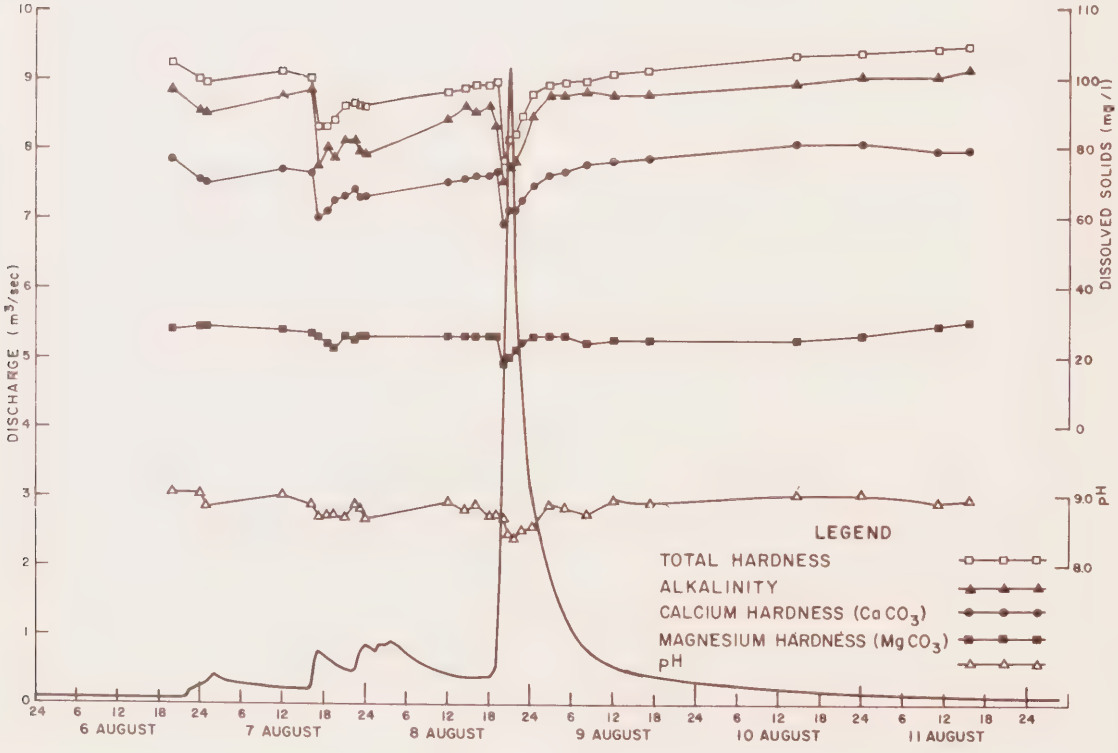


Figure 7. "Twisty Creek" flood hydrochemistry - August 6-11, 1972.

dry period that began in late June. The discharge hydrograph shows a small peak from surface runoff in the immediate vicinity, a rapid increase of discharge from 0.07 to 0.81 m^3/sec in 30 minutes, and a gradual recession lasting for over 24 hours. During this time alkalinity, calcium, magnesium and total hardness concentrations decreased rapidly as the peak discharge was approached, and recovered slowly afterwards.

Closer examination of water chemistry and the discharge hydrograph in Figure 6 reveals several interesting features. The first is the slight rise in pH, calcium and total hardness, and alkalinity at the beginning of the rising stage of the flood. This is a common feature of flood water chemistry and has been noted by a number of researchers. Hem, (1959, p. 278) suggests that the flood wave moving down the channel tends to push water already in the channel ahead of it. Thus, a considerable volume of highly mineralized water accumulates in the wave front, producing a temporary rise in dissolved minerals.

Secondly, the recovery of water chemistry components levelled off about 3.5 h after the peak of the flood and remained fairly constant for at least 3 h afterwards. Samples taken the next day at noon show that a further increase of 5 mg/l for magnesium hardness was the only subsequent increase.

As the chemical properties of water are dependent on the source and the path followed by water, the changes in water chemistry should reflect the relative contribution of groundwater and surface runoff of stream discharge. In an attempt to determine qualitative estimates of these components and to further clarify flood hydrochemistry, care was taken to acquire water samples at the times mentioned during the floods of August 6-11.

Analyses indicate that the small peak at the start of the flood was repeated, as was the rapid decrease and slow recovery which followed (Figure 7). Hardness and alkalinity once again levelled off at 3 to 4 h after the peak, remaining fairly constant until 11 h after the peak, when another change occurred. The discharge recession continued through August 11 with a third change in chemistry occurring after 50 h. Values of pH also changed at the times referred to, and, although apparently complicated by a diurnal decrease around midnight (Figures 6, 7), seem to support the other data.

These observations, as well as data for a number of other floods, have resulted in several suggestions on the source and various components of streamflow in the watershed. Variations in hydrochemistry occurring some 4.5 h after the flood begins (3.5 to 4 h after the peak) are thought to represent the time when the major portion of surface runoff has ceased.

Evidence supporting this point included visual examination of flood recession, as well as the stabilization of water chemistry in the 7 to 8 h which follow. It is also suggested that changes in water chemistry occurring 12 h after the flood begins are due to

the lag time or flow through time of the groundwater system.

5. CONCLUSIONS AND RECOMMENDATIONS

The following observations and tentative conclusions are based on the first season of study of the "Twisty Creek" drainage basin:

1. dissolved material yield was of minor significance;
2. suspended sediment yield for the period was 427,000 kg, of which 93% occurred in a 12 h period on August 8-9;
3. the stream bed is extremely mobile during peak floods;
4. the time base of the major portion of surface runoff and interflow for a flood is of the order of 4 h;
5. spatial and temporal variations in water chemistry can be utilized to suggest source areas of runoff waters and may present an alternative to graphical methods of separation of components of the discharge hydrograph.

A more comprehensive sediment survey program is necessary during the 1973 field season in order to overcome the inadequacies in the methods and results of the present report. Suggestions for improvement in the study of erosion and transport of sediment include:

1. measurement of dissolved material, suspended and bed load at several points in the catchment to study variation of sediment transport within "Twisty Creek";
2. determination of bed load and stream competence from the rate of infilling behind "dams" or nets and movement of dyed or painted samples of bed material;
3. continuation of the water chemistry program to derive rational hydrograph separation techniques.

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